Variability in Compression Strength and Deflection of Corrugated Containers as a Function of Positioning, Operators, and Climatic Conditions

J. SINGH[1,*], P. BAINBRIDGE[2], S. P. SINGH[3] and E. OLSEN[4]

[1]*Associate Professor, Industrial Technology, Cal Poly State University, San Luis Obispo, CA.*

[2]*Research Assistant, Industrial Technology, Cal Poly State University, San Luis Obispo, CA.*

[3]*Professor, School of Packaging, Michigan State University, East Lansing, MI*

[4]*Assistant Professor, Industrial Technology, Cal Poly State University, San Luis Obispo, CA.*

ABSTRACT: ASTM D642 is a commonly used standard for measuring the ability of containers to resist external compressive loads applied to its faces, to diagonally opposite edges, or to corners. The procedure recommends testing by centering the specimen on the lower platen of the testing machine in the desired orientation, so as not to incur eccentric loading. It is also recommended by the standard that the load be applied with a continuous motion of the movable platen of the testing machine at a speed of 0.5 ± 0.1 in. (12.7 ± .25 cm)/min until failure or a specified load, has been reached. It is recommended that the tests be conducted at "standard environmental" conditions of 23°C and 50% relative humidity. However, the vast majority of compression testers are not placed in rooms where humidity is controlled and multiple operators may perform the tests thereby increasing the possibility of variation of reported data. No recent studies involving the effect of variation in the container location or the test speed on the compression strength values, however, are available. This study tested over 400 C-flute RSC style boxes for 15 locations of the containers and ten platen speeds. Repeatability for select test conditions was also tested. The results reported in this paper show a significant reduction in the compression values by as much as 10.7% and an increase in defection by as much as 19.2% for the boxes with the variation in location. Changes in platen velocity and operators significantly affect compression and deflection testing.

*Author to whom correspondence should be addressed. Email: jasingh@calpoly.edu

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1.0 INTRODUCTION

THE role of testing in the development and evaluation of packaging systems has become an important function in today's corporate manufacturing and development practices. The use of lab testing to evaluate the functionality of a product and package is often preferred to real life testing because it can be better controlled and evaluated. Real-life testing, often more representative, is difficult to repeat since the intensity varies with each shipment, and also becomes expensive and time consuming. Various standards organizations use technical committees to develop methodologies that are repeatable and provide a representative simulation of the hazards that will affect a package and the product with a high degree of precision.

The American Standards for Testing and Materials International (ASTM) Committee D-10 is one of the largest sources of packaging test methods both in the United States and overseas. The standards are developed by various technical committees that enjoy a strong participation by industry, federal/state departments, trade organizations and academia. This D-10 committee has been extremely successful in developing a comprehensive set of standards and practices covering both the broad and narrow segments of various aspects of packaging.

ASTM D642, Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads, is a primary test method used to test shipping containers for their ability to resist external compressive loads [1]. This test method is related to Technical Association of the Pulp and Paper Industry (TAPPI) T804, which is similar for fixed platen equipment but does not recognize swivel platen machines [2]. ASTM D648 also fulfills the requirements of International Organization for Standardization (ISO) Test Method 12048 [3].

The ability of a shipping container to resist compressive forces experienced during storage and distribution in the supply chain is often evaluated using a compression tester. Test procedures such as ASTM D642, are typically used to perform laboratory based testing because they implement standardization, may it be within a facility or between different testing labs. This in turn decreases the repeatability and reduces reproducibility errors.

This study was initiated due to a lack of reference studies that reinforce the test procedure described in ASTM D642. Specifically the following steps in the test procedure were targeted for this study:

1. The procedure for compression testing as per ASTM D642 requires centering of the shipping unit on the lower platen of the compression tester in the desired orientation so as not to incur eccentric loading. Although the procedure cautions with regards to obtaining erratic data due to off-centering of the package on the platen, it does not provide references to any studies related to the topic, and the effect of off-centering on measured loads.
2. The procedure also requires the shipping units be tested at the platen speed of 0.5 ± 0.1 in. (12.7 ± 0.25 cm) per minute, whether testing the sample to failure or a specific load. Again, no referenced studies reinforce this.
3. Lastly tests conducted by multiple operators in labs that are generally only controlled for temperature but not for humidity have also not been studied.

The goal of this study was:

1. To study the effect of variation in platen velocity and corrugated box placement on the bottom platen of the compression tester on the measured compression strength and deflection.
2. To study the effect of variation of humidity levels in labs that only have temperature controlled environments using the same boxes but different operators during different parts of the year.

2.0 MATERIALS AND METHODS

A Lansmont Model 152-30 compression test unit was used for this study. This machine was calibrated at the initiation of the study. The servo-hydraulic compression test system used had a 60 inch (1.52 m) square platen, an 84 inch (2.13 m) opening and a maximum force rating of 30,000 pounds (13,608 kg).

Approximately 400, 20″ × 16″ × 10″ (50.8 × 40.6 × 25.4 cm) Regular Slotted Container (RSC) style corrugated shippers were constructed using ArtiosCAD software and Kongsberg sample cutting table. The corrugated board used was 200 pound (90.72 kg) C-flute in construction. The manufacturer's edge on all boxes was sealed with polymer based glue and all flaps were taped using a two inch wide pressure sensitive tape. All shippers were conditioned for 24 hours at 23 ± 1 °C (73.4 ± 2°F) and 50 ± 2 % relative humidity as per ASTM D4332-01 [4].

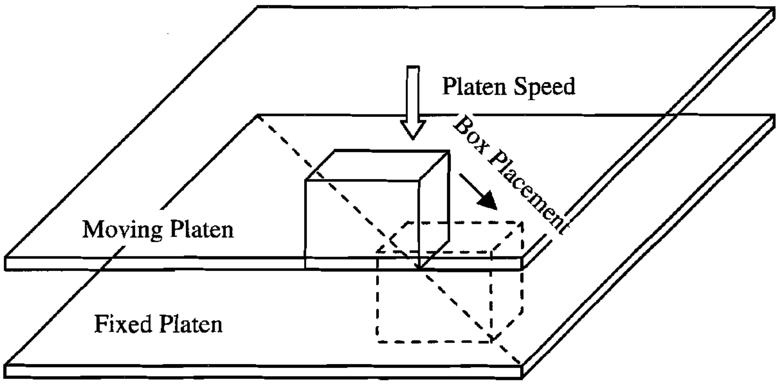

Figure 1. Experimental Setup.

After being formed the compression tests were conducted in a temperature controlled lab. The temperature and humidity conditions associated with the measured values were documented for each box tested.

2.1 Test Method

The corrugated shippers were centered on the diagonal between diagonally opposite corners and moved outwards from the center of the bottom platen in increments of four inches. The platen speed was varied between 0.1 in (0.25 cm) per minute and 1.0 in (2.54 cm) per minute with speed increments of 0.1 in (0.254 cm) per inch. Figure 1 shows the experimental setup.

The test method included of the following steps:

1. Using a plumb line and bob, the boxes were centered at the desired location. The center of the bottom platen was the starting point for all tests and the boxes were moved outwards on one of the diagonal lines between two diagonally opposite corners in increments of four inches (10.2 cm) till 28 inches (71.12 cm) from the center of the platen.
2. Using increments of 0.1 in (0.25 cm) per minute, the platen speed was varied between 0.1 in (0.25 cm) per minute and 1.0 in (2.54 cm) per minute.
3. Compression testing was conducted till failure and the maximum compression strength and deflection measured.
4. Replicates for all variables (box location and test speed) are shown in Table 1.

Table 1. Average Compression and Deflection Chart.

			Distance from Center of Platen (cm)														
			0.0	5.1	10.2	15.2	20.3	25.4	30.5	35.6	40.6	45.7	50.8	55.9	61.0	66.0	71.1
Compression Avg (N)		2867	2968	3010	2830	2845	2930	2894	2900	2948	2903	2783	2946	2839	2691	2833	2651
Deflection Avg (cm)		1.07	0.99	0.99	0.95	1.02	1.00	1.08	1.08	1.14	1.09	1.06	1.19	1.17	1.15	1.08	1.18
Sample size		191	24	8	15	10	15	10	15	10	15	9	15	9	15	7	14
Velocity of Platen (cm/minute)		2556															
	0.25	1.10															
		12	*	*	1	1	1	1	1	1	1	1	1	1	1	*	1
		2732															
	0.51	1.02															
		15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		2827															
	0.76	1.08															
		22	2	1	2	1	2	1	2	1	2	1	2	1	2	*	2
		2848															
	1.02	1.05															
		23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
		2864															
	1.27	1.04															
		33	12	1	2	1	2	1	2	1	2	1	2	1	2	1	2

*Data point removed as outlier. See section on check of regression assumptions.
Temperature range from 17.2°C to 20.3°C with a mean of 19.9.
Humidity from 31.2 to 47.8% RH with a mean of 40.4.

(continued)

Table 1 (continued). *Average Compression and Deflection Chart.*

			Distance from Center of Platen (cm)														
			0.0	**5.1**	**10.2**	**15.2**	**20.3**	**25.4**	**30.5**	**35.6**	**40.6**	**45.7**	**50.8**	**55.9**	**61.0**	**66.0**	**71.1**
Compression Avg (N)		**2867**	**2968**	**3010**	**2830**	**2845**	**2930**	**2894**	**2900**	**2948**	**2903**	**2783**	**2946**	**2839**	**2691**	**2833**	**2651**
Deflection Avg (cm)		**1.07**	**0.99**	**0.99**	**0.95**	**1.02**	**1.00**	**1.08**	**1.08**	**1.14**	**1.09**	**1.06**	**1.19**	**1.17**	**1.15**	**1.08**	**1.18**
Sample size		**191**	**24**	**8**	**15**	**10**	**15**	**10**	**15**	**10**	**15**	**9**	**15**	**9**	**15**	**7**	**14**
Velocity of Platen (cm/minute)	1.52	2913 1.09 23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	1.78	2968 1.06 23	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
	2.03	3048 1.17 14	1	1	1	1	1	1	1	1	1	1	1	1	1	*	1
	2.29	2909 1.09 15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2.54	2933 1.14 11	1	*	1	1	1	1	1	1	1	*	1	*	1	1	*

*Data point removed as outlier. See section on check of regression assumptions.
Temperature range from 17.2°C to 20.3°C with a mean of 19.9.
Humidity from 31.2 to 47.8% RH with a mean of 40.4.

3.0 DATA AND RESULTS

This study examined the effect of platen speed, location of the box, and humidity variations on the compression strength and deflection values resulting from testing the box as representative in a majority of the package testing labs. This section provides the summarized data and statistical analysis of the same.

Deflection is the difference between the box heights at the beginning of the test to that at the end. It is a measure of how much a box is compressed at the end of a test. Compression strength values of packages commonly include the deflection at failure or at the end of a specific load application. The table below shows the average results for compression strength and deflection for a given velocity and location.

The data in Table 1 shows the relationship between the location of the box, the platen speed, and the two dependent variables of interest: compression strength and the deflection. It accounts for the variability of operators and climatic conditions that occurred during the tests. It shows that as the box gets further and further away from the center of the platen, the box defection increases and compressive strength decreases. The data also shows that the velocity of the platen does not greatly affect either deflection or compression strength values. During the four month period of the study, the temperature range varied from 17.2 to 20.3°C with a mean of 19.9°C and the relative humidity ranged from 31.2 to 47.8% with a mean of 40.4%.

3.1 Statistical Analysis

Three analyses pertaining to the study were performed using multivariate statistics. The first involved verifying the repeatability of the tests. The second examined whether the mean velocity of the platen and the distance from the center of the platens significantly affected the compression strength and deflection results. The third analysis examines whether the variability or repeatability of the test is affected by velocity and distance. In all analyses, temperature and humidity were either included in the analysis with no significant effect or treated as random control variables.

3.1.1 Verification of Test Repeatability

To verify that the test results were repeatable, a gage repeatability

ANOVA was run for compression strength and deflection on a subset of the data ($n = 80$) for which two repeated measures were made for each of five platen velocities (45.7 to 106.7 cm/minute) over a range of eight distances (0 to 71cm). The measures made under repeated conditions of velocity and distance were not significantly different for either compression (P = 0.24) or deflection (P = 0.06) indicating that the test is repeatable. The average difference in repeated measures for compression was 99.1 N with a standard deviation of 315.6 and for deflection was 0.072 cm with a standard deviation of 0.26. Temperature and humidity were not explicitly controlled in this analysis, however the non-significant result indicates that repeatability is not affected by temperature and humidity over the range tested.

3.1.2 Test of Platen Velocity and Distance Main Effects

The main objective of this research was to evaluate if the platen velocity and distance from the center have a significant effect on compression and deflection test results. To analyze the effects of velocity and distance a regression model was created with compression and deflection as the dependent variables. The data consisted of 200 individual tests. Table 1 provides a summary of the data. Temperature and humidity entered the model first as control variables. The dependent variables of interest were velocity, distance, and their interaction.

3.1.2.1 Check of Regression Assumptions

Regression assumptions and influential observations were evaluated [5]. Initial regressions were run for compression and deflection, followed by tests for violation of regression assumptions regarding normality, constant variance, and unusual observations and outliers. Nine data points were removed after being identified as unusual based on having high Cook's Distance values relative to the other 191 data points based on examination of box plots. Cook's Distance measures a combination of high leverage and high residual values. Constant variance was verified by examining plots of residuals versus predicted fits. Normal plots of residuals were relatively straight. This observation, along with the large final sample size of 191 data points, makes problems associated with non-normality unlikely.

3.1.2.2 Compression Results

The results of regression analysis are provided in Table 2. Only the

Table 2. *Regression Analysis for Compression.*

Model Summary[c]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.241[a]	0.058	0.048	275.7212	0.058	5.783	2	188	0.004
2	0.424[b]	0.180	0.158	259.3147	0.122	9.181	3	185	0.000

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

ANOVA[c]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	879292.5	2	439646.234	5.783	0.004[a]
	Residual	14292171	188	76022.185		
	Total	15171463	190			
2	Regression	2731304	5	546260.886	8.124	0.000[b]
	Residual	12440159	185	67244.101		
	Total	15171463	190			

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

(continued)

Table 2 (continued). *Regression Analysis for Compression.*

Coefficients[c]

Model		Understandarized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	*t*	Sig.
1	(Constant)	4877.637	795.465		6.132	0.000
	humidity	–21.236	6.350	–0.252	–3.344	0.001
	temperature	–57.853	33.673	–0.129	–1.718	0.087
2	(Constant)	4072.539	797.863		5.104	0.000
	humidity	–13.390	6.396	–0.159	–2.094	0.038
	temperature	–33.999	32.418	–0.076	–1.049	0.296
	velocity	83.507	59.038	0.186	1.414	0.159
	distance	–4.278	2.100	–0.344	–2.037	0.043
	vxd	0.016	0.024	0.133	0.663	0.508

[a]Dependent Variable: Compression

distance from the center of the platen had a significant effect ($p < 0.04$). Velocity of the platen is not significant and no interaction between velocity and distance is evident for the range studied in this experiment and what represents most paper corrugated box test equipment. The overall model is significant and the adjusted R-Sq value is relatively low at 15.8% i.e., the model only explains 15.8% of the variability in the compression test results. Although this may seem like a relatively low value for scientists trying to explain the total compressive strength of a box, it is high for only considering nuisance or control variables. Usually the primary variables of interest are box design, construction, and materials. The model indicates that on average compressive strength is reduced by 4.3 N for each 1 cm the test piece (corrugated box) is off center with all other variables held constant.

3.1.2.3 Deflection Results

The deflection regression analysis results provided in Table 3 are similar to the compression results. Once again only the distance from the center of the platen had a significant effect ($p < 0.004$). Neither the velocity nor the interaction between velocity and distance is significant. The overall model is significant with an adjusted R squared value indicating that the model explains only 9.1% of the variability in the deflection test results. The model indicates that on average deflection is increased by 0.005 cm for each 1 cm the test piece is off center with all other variables held constant.

3.1.3 Test of Platen Velocity and Distance Variance Effects

The question whether the compression and deflection results are more or less variable at various velocity and distance levels is also interesting to researchers. This has implications for test repeatability and reliability. To test for differences in variability Levene's Test of Equality of Error Variances was performed on each dependent variable (i.e. compression and deflection) at all 10 velocity and 15 off-centered distance levels. None of the tests indicated a significant difference in the level of variation. The non-significant result indicates that variation is not affected by temperature and humidity over the range tested.

3.1.4 A Note on Temperature and Humidity

Temperature and humidity were not explicitly examined in this study.

Table 3. *Regression Analysis for Deflection.*

Model Summary[c]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.105[a]	0.011	0.000	0.2209350	0.011	1.043	2	188	0.354
2	0.340[b]	0.115	0.091	0.2106428	0.104	7.274	3	185	0.000

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

ANOVA[c]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.102	2	0.051	1.043	0.354[a]
	Residual	9.177	188	0.049		
	Total	9.279	190			
2	Regression	1.070	5	0.214	4.823	0.000[b]
	Residual	8.209	185	0.044		
	Total	9.279	190			

[a]Predictors: (Constant), temperature humidity
[b]Predictors: (Constant), temperature humidity, distance, velocity, vxd
[c]Dependent Variable: Compression

(continued)

Table 3 (continued). *Regression Analysis for Compression.*

Coefficients[c]

Model		Understandarized Coefficients		Standardized Coefficients		
		B	**Std. Error**	**Beta**	***t***	**Sig.**
1	(Constant)	1.972	0.637		3.094	0.002
	humidity	–0.006	0.005	–0.086	–1.109	0.269
	temperature	–0.034	0.027	–0.096	–1.248	0.214
	(Constant)	1.549	0.648		2.391	0.018
	humidity	–0.003	0.005	–0.050	–0.638	0.524
2	temperature	–0.027	0.026	–0.078	–1.043	0.298
	velocity	0.078	0.048	0.222	1.622	0.107
	distance	0.005	0.002	0.504	2.877	0.004
	vxd	–2.4E-005	0.000	–0.258	–1.239	0.217

[a]Dependent Variable: Compression

However, it is notable that humidity was a significant factor in affecting the compression results and, therefore, was a necessary control factor in the analysis. Humidity in the testing ranged only from 31.2–47.8%. Measured compressive strength decreases by 13.4 N for a one percent increase in humidity. This is the same as a 3.1 cm increase in distance from the center of the platen. Interestingly, humidity was not a significant factor in defection measurements and temperature was not significant in any of the tests.

4.0 CONCLUSIONS

Based on the results of this study it is clear:

1. Compression strength results may vary by as much as 15.8% due to of-center loading and varying platen speed.
2. Variations in humidity (approximately 15%) in labs with "temperature control" only, have a small affect on compression strength results. This is only true for relative humidity of all conditions below 50%.
3. Even though ASTM D642 requires a platen speed of 0.5 ± 0.1 in. (12.7 ± 0.25 cm) per minute, platen speeds between 0.1 (0.25 cm) to 1 in. (2.54 cm) per minute do not produce significant variation in compression strength results.

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