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Effect of Pallet Overhang on Box Compression Strength

Phase 2 Report

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Executive Summary

Accurate estimation of box compression strength is critical for optimizing the performance and safety of global distribution operations. Pallet overhang, a crucial factor affecting box compression strength, has been the subject of limited research. This study aimed to expand on previous findings and strengthen the prediction capabilities of strength loss of boxes when stacked overhanging on a pallet by utilizing an expanded experimental data set and developing a more robust predictive model.

The study used an extensive experimental data set, which included a wide array of corrugated board types, flute types, box dimensions, and overhang magnitudes and directions. Three types of corrugated boards were used: nominal 32 ECT B-flute, nominal 44 ECT C-flute, and nominal 61 ECT C-flute. For each board type, five different box sizes were optimally identified, resulting in a total of 15 box designs. The box dimensions were determined through a space-filling experimental design, with length dimensions between 10 and 24 inches and width and height dimensions between 10 and 20 inches. Overhang was investigated as two continuous variables between 0.25 and 3.25 inches, studying the overhang at the width, the length, or both box sides simultaneously. The data from the previous study (Phase 1) and the current study (Phase 2) were combined to develop a more robust predictive model.

The experimental tests were conducted in a fully randomized order with 10 replicates for each combination, evaluating 90 factor combinations for a total of 900 box compression tests, plus an additional 150 measurements of Box Compression Test (BCT) for the calculation of effective strength loss reduction. Testing was conducted using a compression tester that meets the requirements of ASTM D642 and TAPPI 804 testing standards, and boxes were preconditioned and conditioned according to TAPPI 402 sp-13 specifications. A custom-made 1.5-inch thick rigid plate made of hardwood lumber was used to simulate a pallet and avoid any other pallet-related effects on the box.

A multiple linear regression model (MLR3) was developed using the combined data, which can predict the remaining box compression strength with an R-squared value of 0.867 and a root mean square error (RMSE) of 0.043. The model showed no bias in prediction, with residuals behaving normally

distributed around zero. The height of the box and the Edge Crush Test (ECT) value were found to have no significant effect on the resulting compression strength loss due to overhang, within the ranges studied.

The MLR3 model was validated using an independent data set of 30 commercially available box designs, showing a prediction accuracy of R-squared = 0.707 and RMSE = 0.056. This confirms that the multiple linear regression approach is an acceptable method for estimating the effects of pallet overhang on box compression strength.

The MLR3 model is presented in both metric (Equation 5) and US customary units (Equation 6), providing a simple-to-use tool for practitioners to estimate the effects of pallet overhang on box compression strength. Although more complex models with higher accuracy were explored, the MLR3 model offers a balance between usability and prediction performance.

The study results provide valuable insights into the factors affecting box compression strength loss due to pallet overhang, enabling designers and users to make more informed decisions when developing and optimizing packaging solutions. This research contributes to the development of more efficient and sustainable packaging systems, ultimately improving the performance and safety of global distribution operations.

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1. Introduction

Accurate estimation of box compression strength is critical to optimize the performance and safety of global distribution operations. Publications such as the Fibre Box Handbook (Fibre Box Association, 2018) provide environmental factors for retention analysis that allow designers to estimate the change between the theoretical performance of a box and the performance in the field. Among the environmental factors that have been identified, the overhang of the boxes supported on a pallet stands out as a critical factor and one for which limited research has been conducted (Baker et al., 2016; DiSalvo, 1999; Ievans, 1975; Monaghan & Marcondes, 1992; Singh & Singh, 2011a, 2011b)

Recently our team investigated the effect of pallet overhang on box compression strength, measuring the compression resistance of over 1600 corrugated fiberboard boxes. Our initial findings published by Kim et al. (2023) showed that the effect of overhang on box compression strength could be between a 0% and 40% reduction when compared to the measured box compression strength (BCT), while the current Fibre Box Handbook estimates the reduction to be between 20% and 40% of the original strength. This study investigated four different box dimensions, two board types, and seven overhang levels at the length of the box, the width, and when two sides are overhanging. A multiple regression model was developed using as predictors of the BCT reduction, the overhanging levels on each side of the box, the box perimeter, and the board type. The model proposed can explain 93% of the variability in BCT reduction using the aforementioned variables. While our findings are intriguing and demonstrate a very high potential to estimate BCT reduction due to overhang accurately and reliably, it is limited to the box sizes, styles, and board types tested in the study. Thus, there was an identified critical need to fully characterize the effect of overhang on box compression strength with expanded experimental data that can better represent the wide array of box dimensions, styles and board types commonly found in the field. In the absence of such information, estimation models will only provide limited value to designers and users, continuing to develop suboptimal packages.

This study looks to close the identified gaps between the findings from previous studies and strengthen the prediction capabilities of strength loss of boxes when stacked overhanging on a pallet.

2. Materials, Methods, and Experimental Design

The goal of the project was to expand the data that was used to build the multiple linear regression model to predict the effect of the box overhang on the strength of corrugated boxes developed in Phase 1. The obtained data will be combined with the data obtained in Phase 1 of the study to build a more robust model.

Materials

Corrugated boxes

The samples used in this study were Regular Slotted Container (RSC)style corrugated boxes. Three types of corrugated boards were used for this study: nominal 32 ECT B-flute, nominal 44 ECT C-flute and nominal 61 ECT C-flute. The first phase of the study utilized two types of corrugated board: nominal 32 ECT C-flute and nominal 48 ECT BC-flute. Each board was used to build five different box sizes as shown in Table 1. Box dimensions were determined through an initial space filling experimental design accounting for the 3-dimension variables (length, width, and height) with limits related to commonly available boxes in the distribution environment. Length dimensions were between 10 and 24 inches, width and height dimensions were between 10 and 20. In order to minimize the number of boxes that needed to be manufactured, the researchers simplify the experiment to 15 boxes of different dimensions and board combinations.

The 32 B-flute boxes were manufactured at WestRock Corporation in Mooresville, NC, the 44 C-flute boxes at Pratt Industries, Inc. in Statesville, NC and the 61 C-flute boxes at Packaging Corporation of America in Harrisonburg, VA.

Table 1. Board grades, flutes, and dimensions of the corrugated boxes investigated.

Flute	ECT (lbs./in.)	Length (in.)	Width (in.)	Height (in.)
B	32	18.4	10.5	10.0
B	32	24.0	19.5	20.0
B	32	20.5	20.0	10.0
B	32	13.5	13.5	16.0
B	32	24.0	10.0	20.0
C	44	24.0	16.0	15.0
C	44	24.0	10.0	12.0
C	44	16.3	16.0	20.0
C	44	10.0	10.0	10.0
C	44	16.3	10.0	16.5
C	61	20.5	20.0	18.5
C	61	15.6	15.5	12.5
C	61	10.0	10.0	20.0
C	61	19.8	11.5	20.0
C	61	24.0	18.0	10.0

The manufacturer's joint was sealed using adhesive by the manufacturer. The boxes were shipped knocked down in bundles on a pallet. The top and bottom two boxes in each bundle and any other damaged boxes were removed and discarded to avoid testing boxes with potential damage. Prior to erecting them, the flattened boxes were preconditioned for 24 h in an environment that was between 10% and 30% relative humidity (RH) and between 22C and 40 C and then conditioned at 23C and 50% RH for another 72 h, in compliance with TAPPI T402 (ISO 187). The boxes were erected using a squaring jig to ensure 90 corners. The top and bottom major flaps were sealed to the minor flaps by two parallel beads of 3M™ Hot Melt Adhesive 3762 (3M Corporation, Saint Paul, MN, US) on each section where the flaps met.

Methods

The boxes were tested in a Lansmont Squeezer compression test system equipped with a 5,000 lb. load cell. The tester meets the requirement of ASTM D642 and TAPPI 804 testing standards. The compression tester was calibrated on October 26th, 2023. An adjustable rigid platen was fixed and leveled to provide at least 1:1500 parallelism exceeding the TAPPI requirements. Box compression testing was conducted inside a Conviron CMP5000 walk-in environmental chamber set at 50.0 ± 2.0% relative humidity and 23.0 ± 1.0°C as testing environmental conditions, per TAPPI 402 sp-13 [1] specifications.

Boxes were first preconditioned at 30°C and 20% RH for at least 24 hours. Preconditioning the corrugated board allows for all boxes to reach the equilibrium moisture content through moisture absorption, thus preventing extraneous effects from differences in moisture absorption and desorption. Then, all the materials were conditioned at the test conditions. to validate the equilibrium moisture content of the corrugated board boxes' moisture was intermittently measured immediately after their respective box compression test. These tests were conducted with a Cole-Parmer MP40 Moisture Analyzer. Testing data from compression tests for boxes with moisture content outside of the acceptable range were discarded and retested once the moisture content was equilibrated properly.

To simulate a pallet and to avoid any other pallet-related effect on the box, including the effect of deckboard stiffness and pallet gaps, a custom-made 1.5 in. thick rigid plate made of hardwood lumber was used. The plate was planned to ensure a consistent thickness and parallelism between the top and bottom surfaces. The 1.5 in. thickness allowed enough space for the box corners to deform prior to failure. To ensure the proper placement of the box on the plate, the exact position of the box for each of the tests was clearly marked on the plate. The plate was placed on the bottom platen of the machine, and the box was positioned on top of the plate. The plate and the box were positioned to be centered in the machine. Testing was conducted based on the guidelines of TAPPI T 804 testing standard. The recommended top preload (50 lb. for single wall boxes) was placed on the box, and the box was loaded until visual failure was observed. Boxes were loaded at a constant rate of 0.50 in./min. The deflection and the maximum load at failure were recorded by the compression tester and digitally transferred out of the machine for further analysis.

Overhang was measured perpendicularly to its respective side, length, width, or adjacent. To secure the overhang measurement, two adjustable aluminum guides (Figure 1) were built to ensure a controllable and repeatable overhang magnitude. A Mitutoyo electronic digital caliper was utilized to measure the overhang magnitude. Two individual guides were used for test where both the length and the width of the box were overhanging.

Figure 1. Test setup for box placement with a controllable overhang magnitude.

Experimental Design

This study significantly expanded the experimental space for which the overhang effect had been previously studied. A space filling design using a Fast Flexible Filling (FFF) optimization method was developed. Considering the variables used in the multiple linear regression models presented by Kim et al. (2023) and the fact that a single model for single side and adjacent sides overhang was developed, the overhang was investigated as two continuous variables between ¼ inches and 3 ¼ inches, studying the overhang at the width, the length or both box sides simultaneously. It was considered that smaller overhangs are difficult to control, and larger overhangs would lead to unstable unit loads thus making it unlikely for a designer to build a unit load with such a configuration.

An experimental design using board type (flute and nominal ECT) and dimensions as continuous variables was designed, maximizing the prediction capability of the dataset. Three (3) board types were used. For each board type, five different box dimensions were optimally identified. Boards used were B-flute and C-flute singlewall. To fill the experimental design space evenly, an optimal number of 15 box designs was utilized. Table 2 shows the experimental design for the single overhanging side and Table 3 shows the experimental design for the adjacent side, followed for the model development. The experimental tests were conducted in a fully randomized order with 10 replicates for each of the combinations. The experiment evaluated 90 factor combinations for a total of 900 box compression tests plus an additional 150 measurements of BCT (no overhang) for the calculation of effective strength loss reduction.

Model Validation

To validate the developed model 30 box designs with randomly selected sizes and board combinations were selected from market participants. Each box type was tested using an overhang calculated through a space filling design for the overhang of the width, the length or both sides of the box. Ten replicate tests were conducted for the overhang scenario and 10 replicates for the no overhang. These boxes were not used in the analysis and construction of any prediction model.

Table 2. Experimental design for the evaluation of the overhang scenarios for a single overhanging side.

Flute	ECT (lbs./in.)	Length (in.)	Width (in.)	Height (in.)	Overhang Length (in.)	Overhang Width (in.)	Overhang Side
B	32	13.5	13.5	16.0	1.37	0.00	Length
B	32	13.5	13.5	16.0	2.95	0.00	Length
B	32	18.4	10.5	10.0	1.16	0.00	Length
B	32	18.4	10.5	10.0	2.87	0.00	Length
B	32	20.5	20.0	10.0	1.87	0.00	Length
B	32	20.5	20.0	10.0	2.79	0.00	Length
B	32	24.0	10.0	20.0	0.94	0.00	Length
B	32	24.0	10.0	20.0	2.42	0.00	Length
B	32	24.0	19.5	20.0	0.25	0.00	Length
B	32	24.0	19.5	20.0	3.25	0.00	Length
C	44	10.0	10.0	10.0	0.83	0.00	Length
C	44	10.0	10.0	10.0	3.10	0.00	Length
C	44	16.3	10.0	16.5	1.27	0.00	Length
C	44	16.3	10.0	16.5	2.12	0.00	Length
C	44	16.3	16.0	20.0	1.72	0.00	Length
C	44	16.3	16.0	20.0	2.49	0.00	Length
C	44	24.0	10.0	12.0	0.42	0.00	Length
C	44	24.0	10.0	12.0	2.71	0.00	Length
C	44	24.0	16.0	15.0	0.56	0.00	Length
C	44	24.0	16.0	15.0	2.32	0.00	Length
C	61	10.0	10.0	20.0	2.00	0.00	Length
C	61	10.0	10.0	20.0	2.63	0.00	Length
C	61	15.6	15.5	12.5	0.69	0.00	Length
C	61	15.6	15.5	12.5	2.57	0.00	Length
C	61	19.8	11.5	20.0	1.06	0.00	Length
C	61	19.8	11.5	20.0	3.18	0.00	Length
C	61	20.5	20.0	18.5	1.60	0.00	Length
C	61	20.5	20.0	18.5	3.03	0.00	Length
C	61	24.0	18.0	10.0	1.49	0.00	Length
C	61	24.0	18.0	10.0	2.24	0.00	Length
B	32	13.5	13.5	16.0	0.00	1.36	Width
B	32	13.5	13.5	16.0	0.00	2.66	Width
B	32	18.4	10.5	10.0	0.00	1.99	Width
B	32	18.4	10.5	10.0	0.00	2.57	Width
B	32	20.5	20.0	10.0	0.00	1.85	Width
B	32	20.5	20.0	10.0	0.00	3.25	Width
B	32	24.0	10.0	20.0	0.00	0.65	Width
B	32	24.0	10.0	20.0	0.00	2.48	Width
B	32	24.0	19.5	20.0	0.00	0.41	Width
B	32	24.0	19.5	20.0	0.00	2.32	Width
C	44	10.0	10.0	10.0	0.00	0.52	Width
C	44	10.0	10.0	10.0	0.00	3.10	Width
C	44	16.3	10.0	16.5	0.00	0.89	Width
C	44	16.3	10.0	16.5	0.00	2.10	Width
C	44	16.3	16.0	20.0	0.00	1.13	Width
C	44	16.3	16.0	20.0	0.00	2.93	Width
C	44	24.0	10.0	12.0	0.00	1.48	Width
C	44	24.0	10.0	12.0	0.00	2.22	Width
C	44	24.0	16.0	15.0	0.00	1.02	Width
C	44	24.0	16.0	15.0	0.00	2.40	Width
C	61	10.0	10.0	20.0	0.00	0.25	Width
C	61	10.0	10.0	20.0	0.00	3.02	Width

Flute	ECT (lbs./in.)	Length (in.)	Width (in.)	Height (in.)	Overhang Length (in.)	Overhang Width (in.)	Overhang Side
C	61	15.6	15.5	12.5	0.00	1.23	Width
C	61	15.6	15.5	12.5	0.00	2.85	Width
C	61	19.8	11.5	20.0	0.00	1.72	Width
C	61	19.8	11.5	20.0	0.00	2.16	Width
C	61	20.5	20.0	18.5	0.00	0.77	Width
C	61	20.5	20.0	18.5	0.00	2.75	Width
C	61	24.0	18.0	10.0	0.00	1.60	Width
C	61	24.0	18.0	10.0	0.00	3.18	Width

Table 3. Experimental design for the evaluation of the overhang scenarios for adjacent side overhanging.

Flute	ECT (lbs./in.)	Length (in.)	Width (in.)	Height (in.)	Overhang Length (in.)	Overhang Width (in.)	Overhang Side
B	32	13.5	13.5	16.0	1.92	2.73	Adjacent
B	32	13.5	13.5	16.0	3.01	0.64	Adjacent
B	32	18.4	10.5	10.0	0.42	0.28	Adjacent
B	32	18.4	10.5	10.0	1.03	1.93	Adjacent
B	32	20.5	20.0	10.0	0.56	0.91	Adjacent
B	32	20.5	20.0	10.0	1.42	1.54	Adjacent
B	32	24.0	10.0	20.0	0.49	2.17	Adjacent
B	32	24.0	10.0	20.0	1.62	1.14	Adjacent
B	32	24.0	19.5	20.0	0.26	3.19	Adjacent
B	32	24.0	19.5	20.0	3.20	0.25	Adjacent
C	44	10.0	10.0	10.0	0.31	1.43	Adjacent
C	44	10.0	10.0	10.0	2.58	0.33	Adjacent
C	44	16.3	10.0	16.5	1.33	2.89	Adjacent
C	44	16.3	10.0	16.5	2.04	1.84	Adjacent
C	44	16.3	16.0	20.0	2.35	1.37	Adjacent
C	44	16.3	16.0	20.0	2.80	2.97	Adjacent
C	44	24.0	10.0	12.0	0.75	1.67	Adjacent
C	44	24.0	10.0	12.0	0.94	0.72	Adjacent
C	44	24.0	16.0	15.0	0.87	2.52	Adjacent
C	44	24.0	16.0	15.0	2.90	2.09	Adjacent
C	61	10.0	10.0	20.0	0.66	3.03	Adjacent
C	61	10.0	10.0	20.0	2.13	0.82	Adjacent
C	61	15.6	15.5	12.5	1.21	0.38	Adjacent
C	61	15.6	15.5	12.5	3.24	3.22	Adjacent
C	61	19.8	11.5	20.0	2.74	0.98	Adjacent
C	61	19.8	11.5	20.0	3.13	2.65	Adjacent
C	61	20.5	20.0	18.5	1.76	2.24	Adjacent
C	61	20.5	20.0	18.5	2.49	2.42	Adjacent
C	61	24.0	18.0	10.0	1.82	0.48	Adjacent
C	61	24.0	18.0	10.0	2.22	3.14	Adjacent

3. Results and Discussion

The average reduction of box compression strength, or effective BCT, was calculated for the boxes studied. The average BCT for each studied combination was calculated and the remaining box compression strength $(\boldsymbol{y_i})$ was determined to be used as the main experimental result. Full results are summarized in Appendices 1 and 2 and in the data accompanying the report.

$$\text{Remaining Box Compression Strength } \boldsymbol{y_i} = \frac{\textit{Box Compression Strength with Overhang}}{\textit{Average BCT}}$$

[Equation 1]

Data Exploration of experimental data of phase 2

To better understand the results from the new experimental data collection, the main variables were analyzed. This initial analysis is exclusively focused on the data of Phase 2 (i.e. excluding the results of phase one published by Kim et al. (2023)). Figure 2 shows the frequency distribution of the calculated $\boldsymbol{y_i}$. The data follows a normal distribution with a mean of 0.72 and a standard deviation of 0.12. Given that this is a derived result from 2 test values, the test results for boxes with no overhang, which is equivalent to the box compression strength (BCT) is not included as part of the data set. It is considered that if a box is fully supported, no overhang effect needs to be studied. Additional variable exploration can be conducted by observing the trends between box flutes and the remaining box strength (Figure 3) where no statistical significance is identified between the 2 different flutes studied. Figure 4 shows the relationship between each box studied at the different overhang levels for the short and long side of the box. Under visual inspection, a trend can be observed where the greater overhang in each direction causes a lower remaining box compression strength.

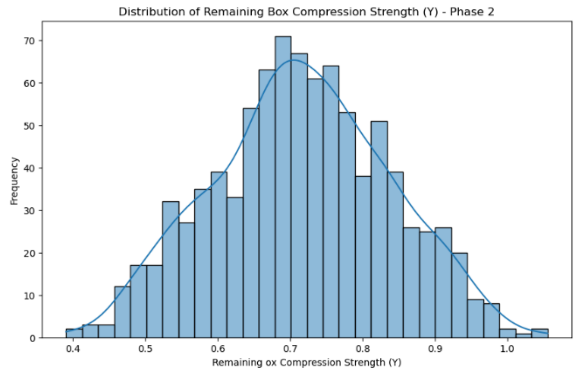


Figure 2. Frequency distribution of remaining box compression strength as a ratio of BCT.

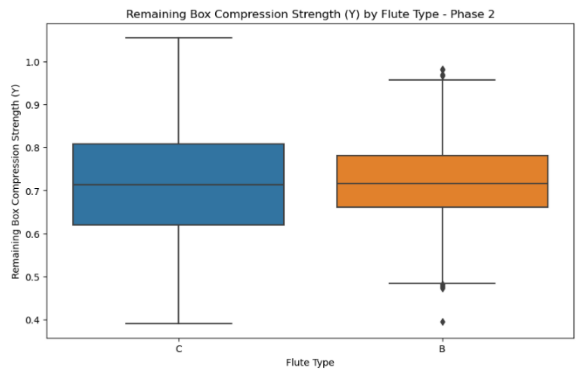
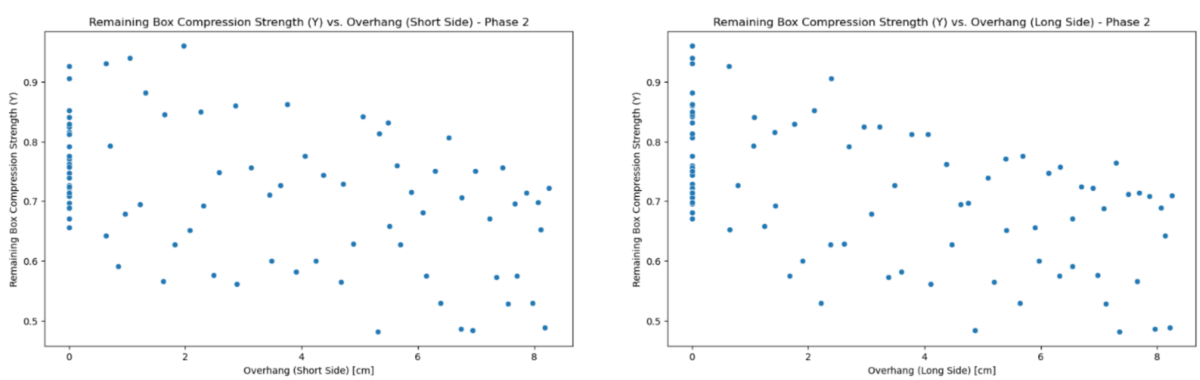


Figure 3. Remaining box compression strength by flute type studied.



(a) (b)

Figure 4. Average remaining box compression strength against overhang on the short side (a) and the long side (b) of the boxes.

Data Exploration of the full data set

As a next step, the data from the previous and the current study were merged for further analysis. As explained in the experimental design, this expanded experimental data set was designed to increase the evaluated regions of the experimental areas, including a wider array of board type measured by the Edge Crush Resistance (ECT), flute type, box dimensions and the overhang magnitude and direction.

Variables x_1 through x_5 were calculated based on the variables presented by Kim et al. (2023), as follows:

x_1: overhang magnitude on the short side of the box(cm)
x_2: overhang magnitude on the long side of the box (cm)
x_3: determines whether there is single side (0) or adjacent overhang(1)
x_4: box perimeter (cm)
x_5: board type, singlewall (0) or doublewall (1) corrugated board (in the previous model, this variable was used to compare C and BC flute)

Some of these variables can be highly dependent on the others. Figure 5 shows the correlation matrix for all the variables evaluated, either from the experimental design or through derived calculations. Clear high correlations are noted for variables that simply represent unit conversions, thus ignored. A slight positive correlation is noted between the box length and width, where most of the larger boxes were bigger on both dimensions. This was especially true in the data set from phase 1 due to the experimental design followed.

Additionally, a negative correlation is observed between the main result (Y) and both overhang magnitudes, at the short and long sides. Moderate correlations exist between the flute type and the ECT of the board. When looking at the variables x_1 through x_5, it is evident that a strong correlation (positive or negative) is present, suggesting that they are still potential predictors for the estimate strength loss of the box compression resistance.

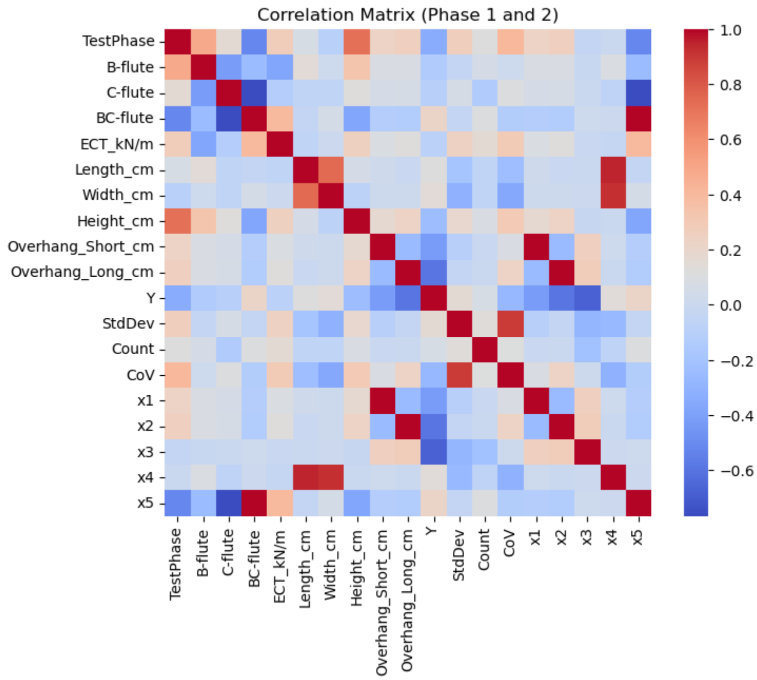


Figure 5. Correlation matrix of the experimental variables included in the study.

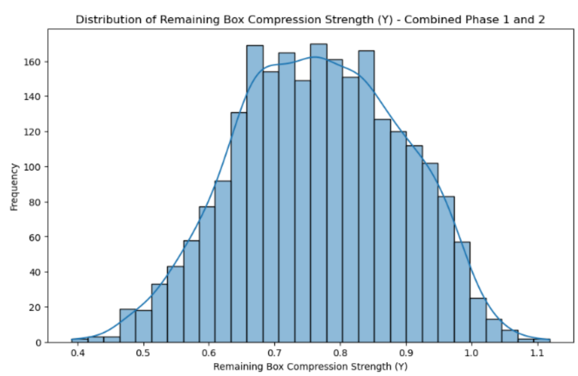


Figure 6. Distribution of frequencies of remaining box compression strength (y) for the combined experimental data.

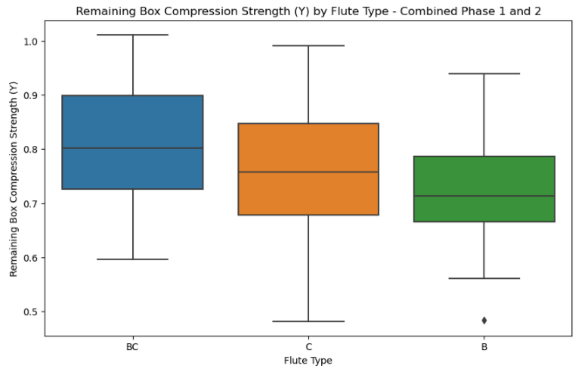


Figure 7. Remaining box compression strength (y) for the combined data versus the flute type of the boxes.

Figure 8 and Figure 9 show the relationship between multiple different continuous variables and the study response. Figure 8 separates the results by 3 colors, each representing the study phases. Phase 3 corresponds to the validation data and is included for visualization purposes. Figure 10 shows a pair plot of all the continuous variables, provided for any further analysis of the experimental data.

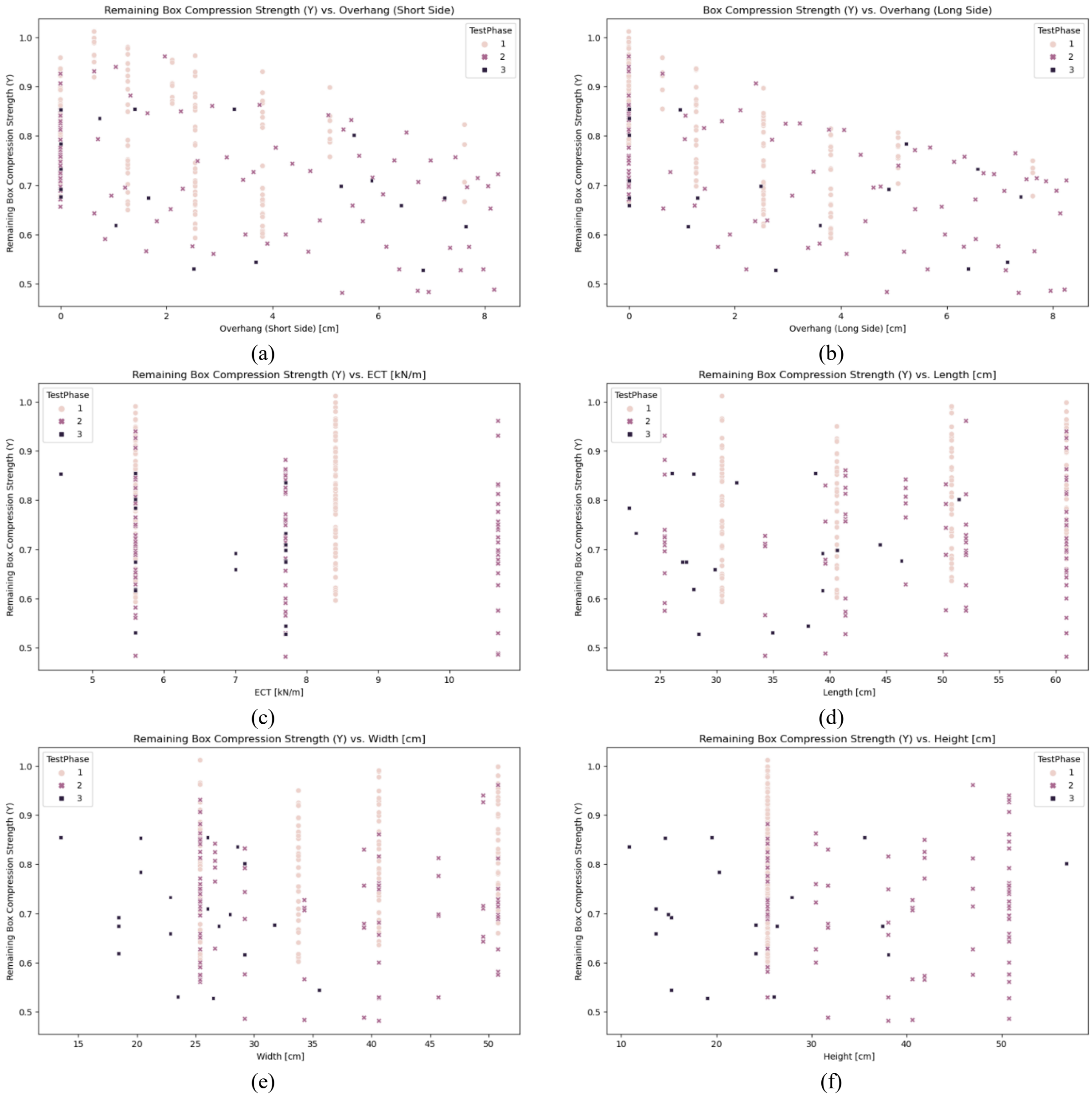


Figure 8. Scatter plots of box compressions strength against multiple continuous variables by test phase.

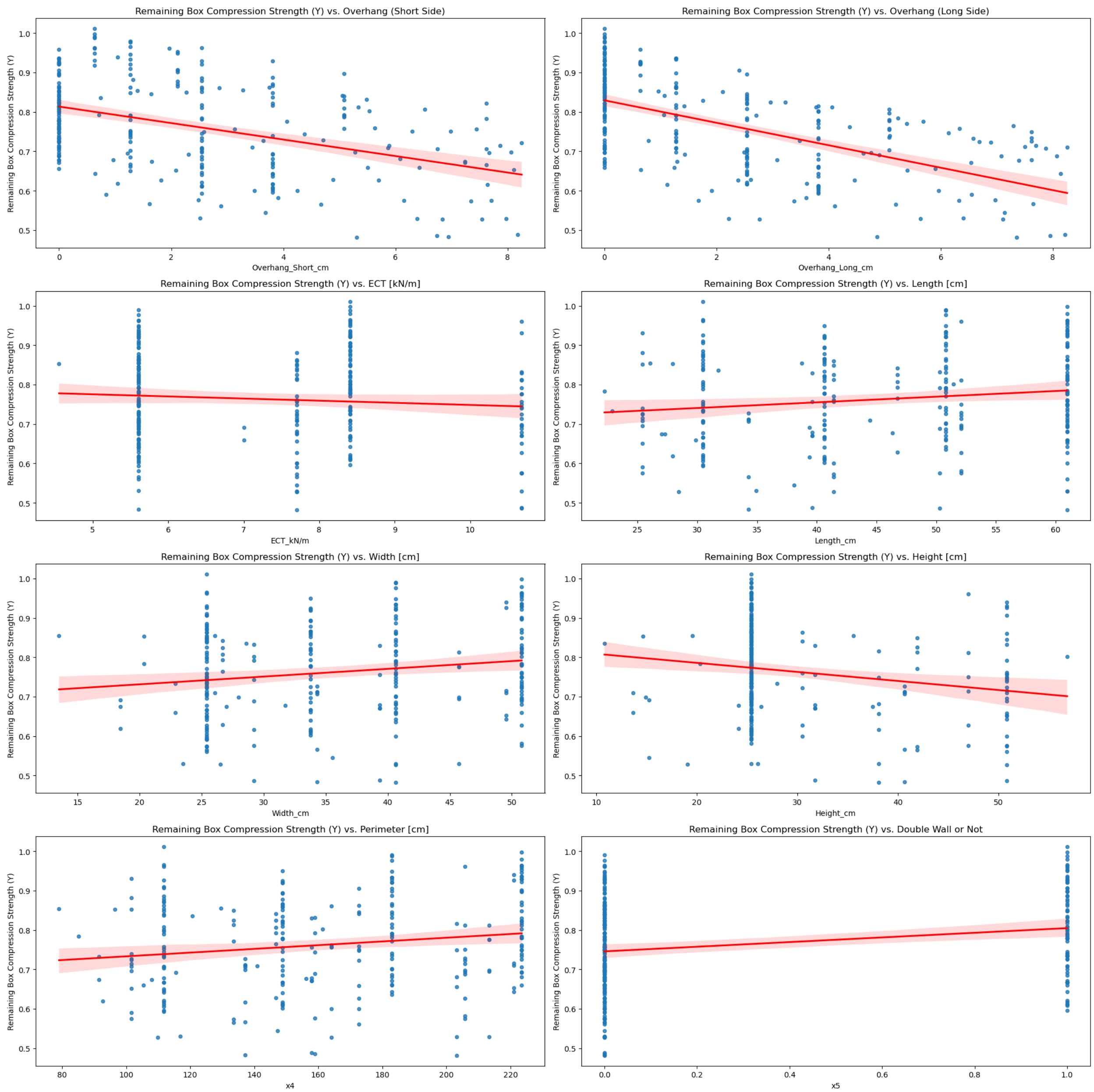


Figure 9. Scatter plots of box compressions strength against multiple continuous variables including a linear best fit line.

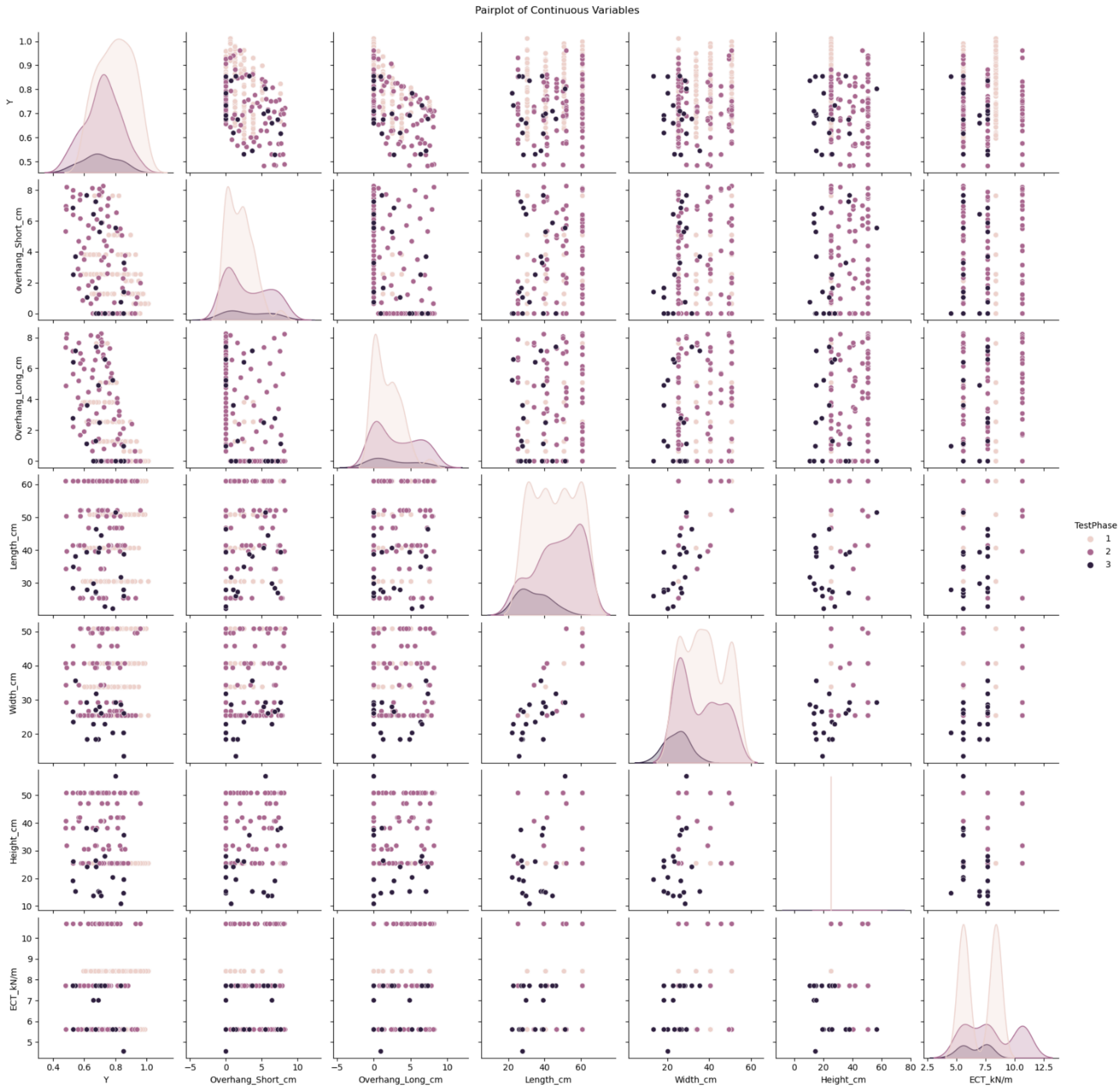


Figure 10. Pair plot of continuous variables included in the study.

Evaluation of the previous model

As a first step before developing a new predictive model for the effect of pallet overhang on box compression strength, the models previously developed by Kim et al. (2023) were evaluated. The three models published had the following expressions:

Multiple Linear Regression Model 1 (MLR1):

$$\hat{y}_i = 0.823 - 0.028x_1 - 0.041x_2 - 0.051x_3 + 0.001x_4 + 0.006x_5$$

[Equation 2]

Non-Linear Regression Model 1 (NLR1):

$$\hat{y}_i = 0.831 - 0.031x_1 - 0.052x_2 + 0.005{x_2}^2 - 0.034x_3 + 0.001x_4 + 0.000004{x_4}^2 + 0.006x_5$$

[Equation 3]

Multiple Linear Regression Model 2 (MLR2):

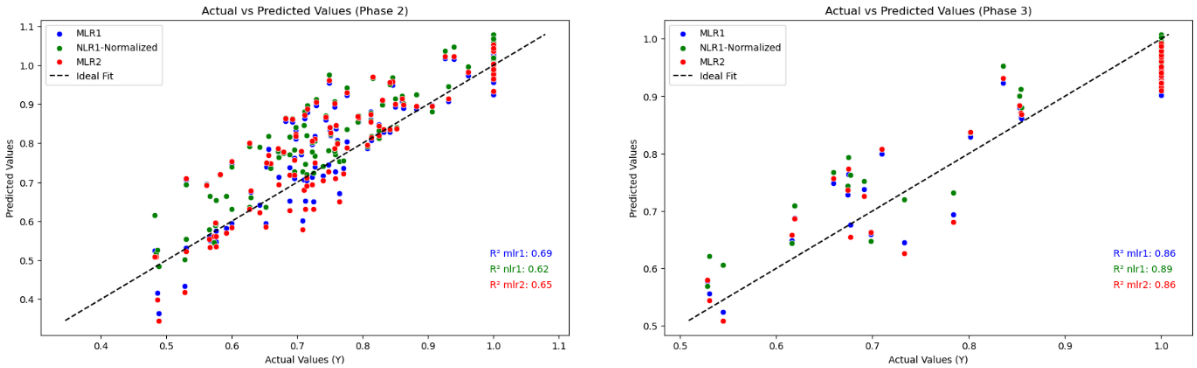
$$\hat{y}_i = 0.831 - 0.028x_1 - 0.045x_2 - 0.045x_3 + 0.001x_4 + 0.006x_5$$

[Equation 4]

Where,

x_1: overhang magnitude on the short side of the box(cm)
x_2: overhang magnitude on the long side of the box (cm)
x_3: determines whether there is single side (0) or adjacent overhang(1)
x_4: box perimeter (cm)
x_5: board type, singlewall (0) or doublewall (1) corrugated board (in the previous model, this variable was used to compare C and BC flute)

Figure 11 (a and b) shows the fit of the three models against the experimental data obtained during the new experimental phase. For the main data set (Phase 2), the best fit was provided by the MLR1 model with a 69% prediction accuracy (R^2). The data from the test data set showed even higher prediction accuracy with an R^2 of 86%. Given the relatively high accuracy and new data, it is necessary to further explore the multiple linear regression models.



(a) (b)

Figure 11. Actual versus predicted values for the evaluation of the original phase 1 models with the new data.

New Multiple Linear Regression Model

Given the relatively high prediction accuracy of the existing model, we began exploring for a better prediction model by including variables that have been provided by the expanded experimental set. These variables include the height of the boxes, where previously only a single box height was investigated, and the ECT for which now multiple combinations of ECT and board type exist. The results for this model are summarized in Table 4. As can be seen, the ECT and box height does not seem to be strong predictors of the overall effect of overhang. After removing the ECT (p-value = 0.89) as a predictor due to the lack of effect in the prediction result, a second model was developed. This model (Table 5) included the height of the box as a predictor. It was hypothesized during the conception of the study that height could play a significant factor in the overhang effect. Given the results (p-value=0.88), it can be concluded that height does not play a significant role in the resulting compression strength loss due to overhang of the boxes. It is worth noting that this result applies exclusively to boxes within the ranges of the values studied (height of the shorter boxes was 10 inches and 20 inches for the largest ones). Different perimeters of boxes were evaluated, so it can be safely concluded that the aspect ratio of the box perimeter and height didn't affect the ultimate loss of strength due to overhang. This result aligns with commonly accepted knowledge of the limited effect of height in box compression strength if the sizes are "common". Similar observations can be made of popular pure box compression strength prediction formulas such as the McKee equation (McKee et al., 1963).

Table 4. Initial multiple regression model including ECT and height.

Effect Summary

Source	LogWorth		PValue
X2_OH_Long_cm	54.403		0.00000
X1_OH_Short_cm	40.760		0.00000
X3_SingleORAdj	33.262		0.00000
X4_Perimeter_cm	8.705		0.00000
X5_Board(DoubleWallOrNot)	2.261		0.00548
ECT	0.073		0.84588
Height	0.053		0.88591

Summary of Fit

RSquare	0.867304
RSquare Adj	0.863334
Root Mean Square Error	0.043257
Mean of Response	0.767694
Observations (or Sum Wgts)	242

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	2.8617588	0.408823	218.4897
Error	234	0.4378446	0.001871	**Prob > F**
C. Total	241	3.2996034		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8475862	0.018276	46.38	<.0001*
X1_OH_Short_cm	-0.02344	0.00141	-16.62	<.0001*
X2_OH_Long_cm	-0.029401	0.001413	-20.80	<.0001*
X3_SingleORAdj	-0.095823	0.006669	-14.37	<.0001*
X4_Perimeter_cm	0.0004309	0.000069	6.25	<.0001*
X5_Board(DoubleWallOrNot)	0.0221953	0.007917	2.80	0.0055*
ECT	-6.85e-5	0.000352	-0.19	0.8459
Height	0.0001384	0.000963	0.14	0.8859

Table 5. Second multiple regression model including only ECT.

Effect Summary

Source	LogWorth	PValue
X2_OH_Long_cm	55.758	0.00000
X1_OH_Short_cm	41.574	0.00000
X3_SingleORAdj	33.755	0.00000
X4_Perimeter_cm	8.742	0.00000
X5_Board(DoubleWallOrNot)	2.663	0.00217
ECT	0.055	0.88123

Summary of Fit

RSquare	0.867292
RSquare Adj	0.863904
Root Mean Square Error	0.043166
Mean of Response	0.767694
Observations (or Sum Wgts)	242

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	2.8617202	0.476953	255.9679
Error	235	0.4378832	0.001863	**Prob > F**
C. Total	241	3.2996034		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8484108	0.017314	49.00	<.0001*
X1_OH_Short_cm	-0.023408	0.001389	-16.85	<.0001*
X2_OH_Long_cm	-0.029363	0.001385	-21.20	<.0001*
X3_SingleORAdj	-0.09593	0.006613	-14.51	<.0001*
X4_Perimeter_cm	0.000431	6.884e-5	6.26	<.0001*
X5_Board(DoubleWallOrNot)	0.0216652	0.00699	3.10	0.0022*
ECT	-0.000048	0.000321	-0.15	0.8812

Table 6. Third multiple regression model without additional predictors.

Effect Summary

Source	LogWorth		PValue
X2_OH_Long_cm	59.350		0.00000
X1_OH_Short_cm	44.108		0.00000
X3_SingleORAdj	34.592		0.00000
X4_Perimeter_cm	8.807		0.00000
X5_Board(DoubleWallOrNot)	3.167		0.00068

Summary of Fit

RSquare	0.86728
RSquare Adj	0.864468
Root Mean Square Error	0.043077
Mean of Response	0.767694
Observations (or Sum Wgts)	242

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	2.8616785	0.572336	308.4347
Error	236	0.4379249	0.001856	**Prob > F**
C. Total	241	3.2996034		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.8466809	0.012858	65.85	<.0001*	0.82135	0.872012
X1_OH_Short_cm	-0.023465	0.001334	-17.59	<.0001*	-0.02609	-0.02084
X2_OH_Long_cm	-0.029425	0.001319	-22.32	<.0001*	-0.03202	-0.02683
X3_SingleORAdj	-0.095754	0.006494	-14.75	<.0001*	-0.10855	-0.08296
X4_Perimeter_cm	0.0004314	6.863e-5	6.29	<.0001*	0.000296	0.000567
X5_Board(DoubleWallOrNot)	0.0211718	0.006149	3.44	0.0007*	0.009057	0.033287

Updated Multiple Linear Regression Model 3 (MLR3):

$$\hat{y}_i = 0.8467 - 0.0235x_1 - 0.0294x_2 - 0.0958x_3 + 0.0004x_4 + 0.0212x_5$$

[Equation 5]

More in-depth analysis of the updated model (MLR3; Equation 5) was conducted. The prediction fit can be assessed on Figure 12, with a Root Mean Square Error (RMSE) of 0.043. Figure 13 demonstrates that there is no bias in the prediction where the residuals do not show any trend and behave normally distributed around zero.

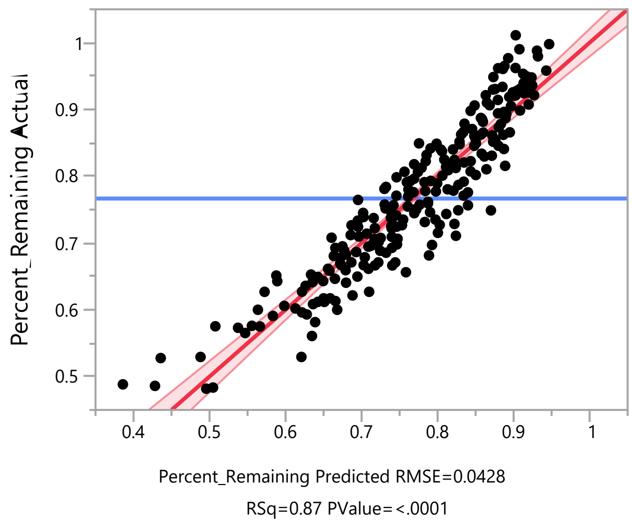
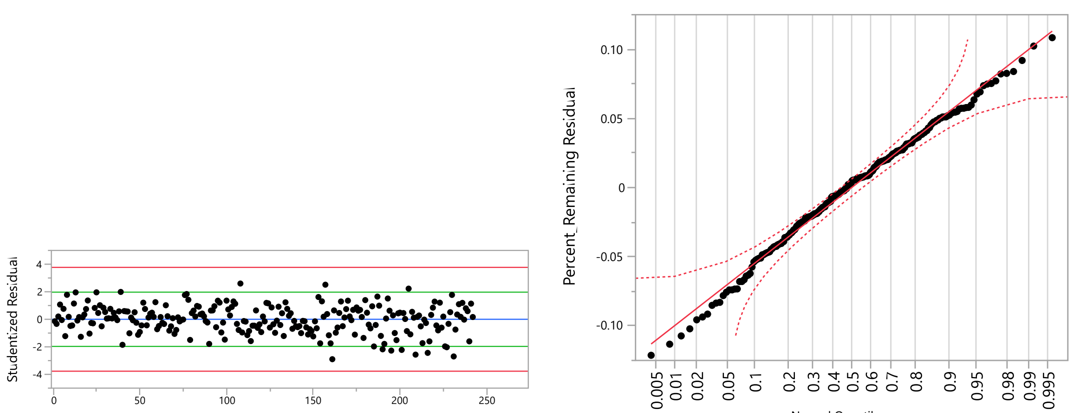


Figure 12. Prediction vs Actual results for the multiple linear regression model 3 with the training data.



Externally studentized residuals with 95% simultaneous limits (Bonferroni) in red, individual limits in green.
Externally studentized residuals with 95% simultaneous limits (Bonferroni) in red, individual limits in green.

Figure 13. Studentized residuals for the MLR3 model prediction and Normal Quantile plot for the prediction residuals.

Figure 14 shows the accumulated results for the Cook's Distance evaluation. This value provides a measurement of the influence of data points in the prediction model. It is commonly accepted that values over 1.0 are considered problematic and influencing the prediction model. Higher than 0.5 are to be further investigated. Based on the experimental design and results obtained, no data points are considered highly influential, as the highest Cook's distance was 0.08 for 1 data point. Figure 15 shows the leverage plots for the five predictors. No data points stand out as being overleveraged.

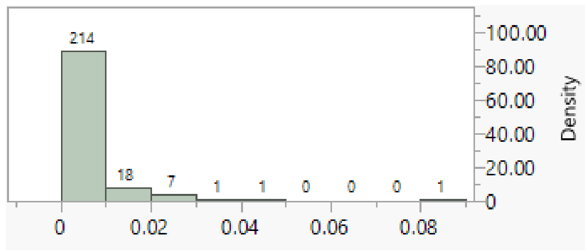


Figure 14. Cook's Distance results for the influence evaluation of the data set.

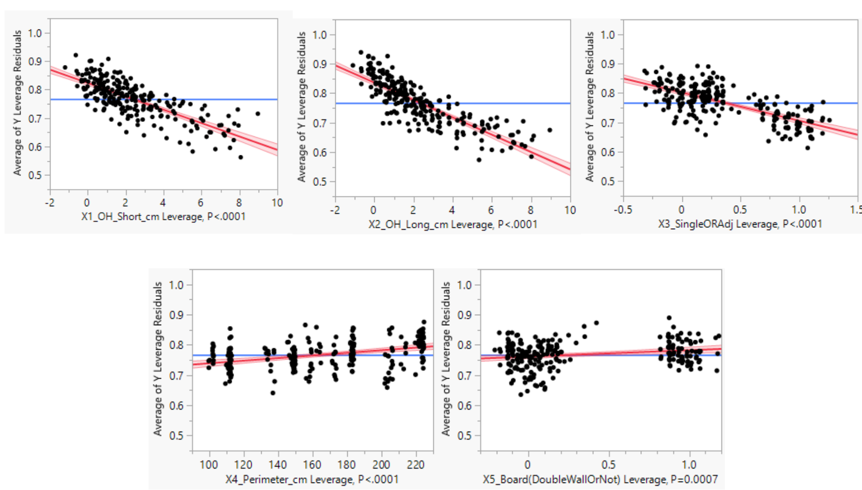


Figure 15. Leverage plots for each of the five predictors.

Multiple Linear Regression Model 3 in US Customer Units

Given the importance of developing a model that can be widely adopted in the United States, Equation 6 presents the prediction expression of the developed model when inputting values with US customary units, with all distance measurements in inches.

$$\hat{y}_i[US\ Customary\ Units] = 0.8504 - 0.05960 - 0.0742\mathrm{x}_2 - 0.0962\mathrm{x}_3 + 0.0010\mathrm{x}_4 + 0.0231\mathrm{x}_5$$

[Equation 6]

Where,
x_1: overhang magnitude on the short side of the box(inches)
x_2: overhang magnitude on the long side of the box (inches)
x_3: determines whether there is single side (0) or adjacent overhang(1)
x_4: box perimeter (inches)
x_5: board type, singlewall (0) or doublewall (1) corrugated board (in the previous model, this variable was used to compare C and BC flute)

Model validation with independent data set

Figure 17 and Table 7 show the prediction capabilities of the new model compared against a randomly selected data set of commercially available boxes. The model could predict the results with an R^2 of 0.707 and a RMSE of 0.056. Overall, this prediction accuracy confirms that the multiple linear regression is an acceptable approach to estimate the effects from pallet overhang on box compression strength. Even though additional, more complex models can be developed, it is considered that a simple to use model will provide more usefulness to practitioners than a slightly better fit that requires higher computing power and complexity.

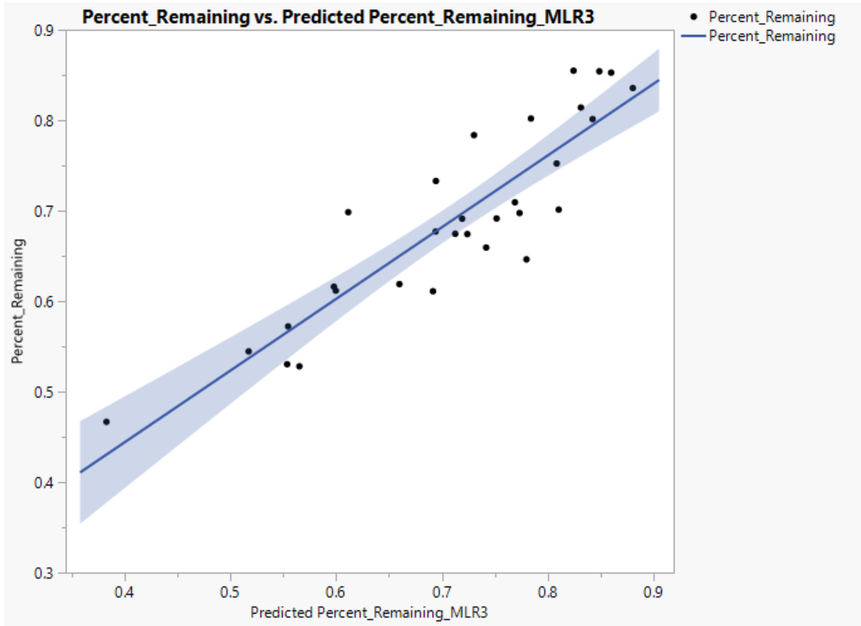


Figure 16. Prediction vs Actual results for the multiple linear regression model 3 with the validation (test) data of phase 3.

Table 7. Actual results of the validation boxes data set versus prediction from the updated multiple regression model.

Test Phase	Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Percent Remaining	Predicted Percent Remaining MLR3	Error MLR3	Predicted Percent Remaining Model4	Error Model 4
3	C	32	15.25	10.06	14.00	2.69	1.09	Adjacent	0.53	0.57	-0.04	0.55	-0.02
3	C	32	10.38	10.63	14.75	2.85	0.00	Short	0.67	0.72	-0.05	0.72	-0.05
3	C	44	17.63	10.25	5.38	2.32	0.00	Short	0.71	0.77	-0.06	0.77	-0.06
3	C	44	16.00	11.00	5.88	2.09	0.99	Adjacent	0.70	0.61	0.09	0.59	0.11
3	B	26	11.00	8.00	5.75	0.00	0.38	Long	0.85	0.86	-0.01	0.86	-0.01
3	C	40	11.75	9.00	5.38	2.54	0.00	Short	0.66	0.74	-0.08	0.74	-0.08
3	B	32	13.50	9.00	10.63	0.00	0.86	Long	0.81	0.83	-0.02	0.81	0.00
3	C	32	15.50	11.50	15.00	3.01	0.44	Adjacent	0.62	0.60	0.02	0.60	0.01
3	C	40	18.25	12.75	7.63	0.00	0.94	Long	0.80	0.84	-0.04	0.82	-0.02
3	C	44	10.75	7.25	10.38	0.66	0.52	Adjacent	0.67	0.71	-0.04	0.73	-0.05
3	C	32	15.25	10.25	14.00	1.30	0.00	Short	0.85	0.82	0.03	0.83	0.03
3	B	32	20.13	11.50	22.25	2.19	0.00	Short	0.80	0.78	0.02	0.78	0.02
3	C	250#	9.00	9.00	11.00	0.00	2.59	Long	0.73	0.69	0.04	0.70	0.04
3	C	200#	14.75	14.00	6.13	1.46	2.81	Adjacent	0.54	0.52	0.03	0.54	0.00
3	C	44	12.50	11.25	4.25	0.29	0.00	Short	0.84	0.88	-0.05	0.90	-0.06
3	C	32	13.75	9.25	10.25	1.00	2.53	Adjacent	0.53	0.55	-0.02	0.57	-0.04
3	C	275#	18.13	12.00	9.25	0.00	2.92	Long	0.68	0.69	-0.02	0.72	-0.04
3	C	32	10.25	5.31	7.69	0.55	0.00	Short	0.85	0.85	0.01	0.86	-0.01
3	C	40	15.50	7.13	5.75	0.00	1.94	Long	0.69	0.75	-0.06	0.73	-0.04
3	C	32	11.00	7.25	9.50	0.42	1.43	Adjacent	0.62	0.66	-0.04	0.66	-0.04
3	C	32	8.75	8.00	8.00	0.00	2.07	Long	0.78	0.73	0.05	0.71	0.07
3	C	32	26.00	19.00	5.25	2.25	0.00	Short	0.70	0.77	-0.08	0.76	-0.06
3	C	32	19.25	14.50	11.07	1.75	2.21	Adjacent	0.57	0.55	0.02	0.54	0.03
3	C	200#	13.00	11.00	4.50	0.00	1.21	Long	0.75	0.81	-0.06	0.78	-0.03
3	E	32	19.50	10.50	8.50	1.65	1.58	Adjacent	0.61	0.60	0.01	0.58	0.03
3	E	32	13.50	10.00	12.00	1.17	0.00	Short	0.70	0.81	-0.11	0.78	-0.08
3	C	275#	9.25	7.75	7.50	2.60	0.00	Short	0.61	0.69	-0.08	0.69	-0.08
3	B	NA	11.50	8.00	5.50	3.11	3.05	Adjacent	0.47	0.38	0.08	0.43	0.04
3	C	NA	14.50	10.00	12.00	0.00	2.43	Long	0.69	0.72	-0.03	0.71	-0.02
3	C	NA	13.00	10.00	11.00	0.00	1.97	Long	0.65	0.78	-0.13	0.78	-0.13

4. Conclusions

- The expanded experimental data set, which included a wider array of board types, flute types, box dimensions, and overhang magnitudes and directions, allowed for the development of a more robust predictive model for estimating the effect of pallet overhang on box compression strength.
- The multiple linear regression model (MLR3) developed using the combined data from Phase 1 and Phase 2 can predict the remaining box compression strength with an R-squared value of 0.867 and a root mean square error (RMSE) of 0.043. This model shows no bias in prediction, with residuals behaving normally distributed around zero.
- The height of the box and the Edge Crush Test (ECT) value were found to have no significant effect on the resulting compression strength loss due to overhang, within the ranges studied. This aligns with the commonly accepted knowledge of the limited effect of height on box compression strength for "common" box sizes.
- The validation of the MLR3 model using an independent data set of commercially available boxes showed a prediction accuracy of R-squared = 0.834 and RMSE = 0.04. This confirms that the multiple linear regression approach is an acceptable method for estimating the effects of pallet overhang on box compression strength.
- The MLR3 model, presented in both metric (Equation 5) and US customary units (Equation 6), provides a simple-to-use tool for practitioners to estimate the effects of pallet overhang on box compression strength. Although more complex models with higher accuracy were explored, the MLR3 model offers a balance between usability and prediction performance.
- The study results provide valuable insights into the factors affecting box compression strength loss due to pallet overhang, enabling designers and users to make more informed decisions

when developing and optimizing packaging solutions.

5. Bibliography

Baker, M., Horvath, L., & White, M. S. (2016). Predicting the effect of gaps between pallet deckboards on the compression strength of corrugated boxes. *Journal of Applied Packaging Research*, *8*(3), Article 3. https://doi.org/10.14448/japr.08.0017

DiSalvo, M. H. (1999). *Interactive effects of palletizing factors on fiberboard packing strength* [Master's Thesis]. San Jose State University.

Fibre Box Association. (2018). *Fibre Box Handbook* (Vol. 1).

Ievans, U. I. (1975). The effect of warehouse mishandling and stacking patterns on the compression strength of corrugated boxes. *TAPPI Journal*, *58*(8), 108–111.

Kim, S., Horvath, L., Molina, E., Frank, B., Johnson, S., & Johnson, A. (2023). Predicting the effect of pallet overhang on the box compression strength. *Packaging Technology and Science*, pts.2768. https://doi.org/10.1002/pts.2768

McKee, R. C., Ganer, J. W., & Wachuta, J. R. (1963). Compression strenght formula for corrugated boxes. In G. G. Maltenfort (Ed.), *Performance and Evaluation of Shipping Containers* (pp. 62–73). Jelmar Publishing Co., Inc.

Monaghan, J., & Marcondes, J. (1992). Technical notes: Overhang and pallet gap effects on the performance of corrugated fiberboard boxes. *Transactions of the ASAE*, *35*(6), Article 6. https://doi.org/10.13031/2013.28820

Singh, J., & Singh, S. P. (2011a). *Effect of Horizontal Offset on Vertical Compression Strength of Stacked Corrugated Fiberboard Boxes* (3). *5*(3), Article 3.

Singh, J., & Singh, S. P. (2011b). Effect of Palletized Box Offset on Compression Strength of

Unitized and Stacked Empty Corrugated Fiberboard Boxes. *Journal of Applied Packaging Research*, *5*(3), Article 3.

Appendix 1. Averaged box compression remaining strength for the boxes studied in phase 2.

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
B	32	13.5	13.5	16.0	0.00	0.00	No Overhang	489.64	1.00	10	0.05	5.06
B	32	13.5	13.5	16.0	0.00	1.37	Long	356.03	0.73	10	0.04	5.51
B	32	13.5	13.5	16.0	0.00	2.95	Long	348.57	0.71	10	0.03	3.78
B	32	13.5	13.5	16.0	0.64	3.01	Adjacent	277.23	0.57	10	0.03	4.94
B	32	13.5	13.5	16.0	1.36	0.00	Short	348.05	0.71	10	0.06	8.91
B	32	13.5	13.5	16.0	2.66	0.00	Short	345.83	0.71	10	0.03	4.37
B	32	13.5	13.5	16.0	2.73	1.92	Adjacent	236.74	0.48	10	0.04	7.83
B	32	18.4	10.5	10.0	0.00	0.00	No Overhang	489.17	1.00	10	0.07	7.29
B	32	18.4	10.5	10.0	0.00	1.16	Long	403.29	0.82	10	0.08	9.63
B	32	18.4	10.5	10.0	0.00	2.87	Long	373.99	0.76	10	0.07	9.60
B	32	18.4	10.5	10.0	0.28	0.42	Adjacent	387.93	0.79	10	0.07	8.22
B	32	18.4	10.5	10.0	1.93	1.03	Adjacent	307.47	0.63	10	0.05	7.34
B	32	18.4	10.5	10.0	1.99	0.00	Short	411.75	0.84	10	0.06	6.65
B	32	18.4	10.5	10.0	2.57	0.00	Short	394.62	0.81	10	0.07	8.55
B	32	20.5	20.0	10.0	0.00	0.00	No Overhang	499.14	1.00	10	0.03	2.62
B	32	20.5	20.0	10.0	0.00	1.87	Long	347.94	0.70	10	0.04	5.06
B	32	20.5	20.0	10.0	0.00	2.79	Long	343.57	0.69	10	0.03	4.69
B	32	20.5	20.0	10.0	0.91	0.56	Adjacent	345.77	0.69	10	0.03	4.81
B	32	20.5	20.0	10.0	1.54	1.42	Adjacent	290.25	0.58	10	0.03	4.67
B	32	20.5	20.0	10.0	1.85	0.00	Short	363.65	0.73	10	0.03	4.31
B	32	20.5	20.0	10.0	3.25	0.00	Short	360.42	0.72	10	0.03	3.80
B	32	24.0	10.0	20.0	0.00	0.00	No Overhang	411.79	1.00	10	0.07	7.10
B	32	24.0	10.0	20.0	0.00	0.94	Long	373.08	0.91	10	0.05	5.69
B	32	24.0	10.0	20.0	0.00	2.42	Long	307.68	0.75	10	0.05	6.10
B	32	24.0	10.0	20.0	0.65	0.00	Short	348.25	0.85	10	0.05	6.35
B	32	24.0	10.0	20.0	1.14	1.62	Adjacent	230.91	0.56	10	0.05	9.27

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
B	32	24.0	10.0	20.0	2.17	0.49	Adjacent	271.21	0.66	10	0.03	3.95
B	32	24.0	10.0	20.0	2.48	0.00	Short	308.91	0.75	10	0.05	6.78
B	32	24.0	19.5	20.0	0.00	0.00	No Overhang	507.01	1.00	10	0.10	9.76
B	32	24.0	19.5	20.0	0.00	0.25	Long	469.37	0.93	10	0.03	2.91
B	32	24.0	19.5	20.0	0.00	3.25	Long	359.81	0.71	10	0.04	5.17
B	32	24.0	19.5	20.0	0.25	3.20	Adjacent	325.91	0.64	10	0.03	4.39
B	32	24.0	19.5	20.0	0.41	0.00	Short	476.36	0.94	10	0.03	3.02
B	32	24.0	19.5	20.0	2.32	0.00	Short	362.62	0.72	10	0.02	3.24
B	32	24.0	19.5	20.0	3.19	0.26	Adjacent	330.95	0.65	10	0.04	6.50
C	44	10.0	10.0	10.0	0.00	0.00	No Overhang	574.83	1.00	10	0.06	5.77
C	44	10.0	10.0	10.0	0.00	0.83	Long	489.59	0.85	10	0.07	8.50
C	44	10.0	10.0	10.0	0.00	3.10	Long	406.94	0.71	10	0.06	8.91
C	44	10.0	10.0	10.0	0.33	2.58	Adjacent	339.60	0.59	10	0.04	6.55
C	44	10.0	10.0	10.0	0.52	0.00	Short	506.74	0.88	10	0.05	5.45
C	44	10.0	10.0	10.0	1.43	0.31	Adjacent	417.63	0.73	10	0.06	8.58
C	44	10.0	10.0	10.0	3.10	0.00	Short	410.59	0.71	10	0.06	8.24
C	44	16.3	10.0	16.5	0.00	0.00	No Overhang	707.10	1.00	10	0.07	7.32
C	44	16.3	10.0	16.5	0.00	1.27	Long	583.31	0.82	10	0.07	8.95
C	44	16.3	10.0	16.5	0.00	2.12	Long	545.06	0.77	10	0.06	7.98
C	44	16.3	10.0	16.5	0.89	0.00	Short	600.58	0.85	10	0.03	3.73
C	44	16.3	10.0	16.5	1.84	2.04	Adjacent	399.65	0.57	10	0.04	7.88
C	44	16.3	10.0	16.5	2.10	0.00	Short	574.71	0.81	10	0.03	3.53
C	44	16.3	10.0	16.5	2.89	1.33	Adjacent	405.18	0.57	10	0.04	7.71
C	44	16.3	16.0	20.0	0.00	0.00	No Overhang	798.38	1.00	10	0.05	4.64
C	44	16.3	16.0	20.0	0.00	1.72	Long	608.01	0.76	10	0.07	8.85
C	44	16.3	16.0	20.0	0.00	2.49	Long	604.85	0.76	10	0.07	9.28
C	44	16.3	16.0	20.0	1.13	0.00	Short	686.94	0.86	10	0.07	8.47
C	44	16.3	16.0	20.0	1.37	2.35	Adjacent	479.03	0.60	10	0.04	6.39

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
C	44	16.3	16.0	20.0	2.93	0.00	Short	604.02	0.76	10	0.06	8.31
C	44	16.3	16.0	20.0	2.97	2.80	Adjacent	421.28	0.53	10	0.04	8.46
C	44	24.0	10.0	12.0	0.00	0.00	No Overhang	753.78	1.00	10	0.08	7.70
C	44	24.0	10.0	12.0	0.00	0.42	Long	633.79	0.84	10	0.07	8.04
C	44	24.0	10.0	12.0	0.00	2.71	Long	544.43	0.72	10	0.06	8.25
C	44	24.0	10.0	12.0	0.72	0.94	Adjacent	472.57	0.63	10	0.06	8.82
C	44	24.0	10.0	12.0	1.48	0.00	Short	650.13	0.86	10	0.06	7.53
C	44	24.0	10.0	12.0	1.67	0.75	Adjacent	452.27	0.60	10	0.04	6.57
C	44	24.0	10.0	12.0	2.22	0.00	Short	572.39	0.76	10	0.03	4.53
C	44	24.0	16.0	15.0	0.00	0.00	No Overhang	1038.90	1.00	10	0.07	6.58
C	44	24.0	16.0	15.0	0.00	0.56	Long	847.28	0.82	10	0.08	9.93
C	44	24.0	16.0	15.0	0.00	2.32	Long	681.72	0.66	10	0.06	9.63
C	44	24.0	16.0	15.0	1.02	0.00	Short	777.99	0.75	10	0.06	8.17
C	44	24.0	16.0	15.0	2.09	2.90	Adjacent	500.54	0.48	10	0.04	7.71
C	44	24.0	16.0	15.0	2.40	0.00	Short	707.90	0.68	10	0.04	5.34
C	44	24.0	16.0	15.0	2.52	0.87	Adjacent	549.95	0.53	10	0.02	4.01
C	61	10.0	10.0	20.0	0.00	0.00	No Overhang	933.66	1.00	10	0.08	7.80
C	61	10.0	10.0	20.0	0.00	2.00	Long	690.37	0.74	10	0.06	8.01
C	61	10.0	10.0	20.0	0.00	2.63	Long	676.18	0.72	10	0.07	9.31
C	61	10.0	10.0	20.0	0.25	0.00	Short	868.86	0.93	10	0.06	6.98
C	61	10.0	10.0	20.0	0.82	2.13	Adjacent	608.09	0.65	10	0.06	8.96
C	61	10.0	10.0	20.0	3.02	0.00	Short	649.58	0.70	10	0.05	7.07
C	61	10.0	10.0	20.0	3.03	0.66	Adjacent	536.80	0.57	10	0.04	7.31
C	61	15.6	15.5	12.5	0.00	0.00	No Overhang	1241.68	1.00	10	0.03	3.04
C	61	15.6	15.5	12.5	0.00	0.69	Long	1030.05	0.83	10	0.03	3.25
C	61	15.6	15.5	12.5	0.00	2.57	Long	833.15	0.67	10	0.05	7.01
C	61	15.6	15.5	12.5	0.38	1.21	Adjacent	842.72	0.68	10	0.04	6.19
C	61	15.6	15.5	12.5	1.23	0.00	Short	939.23	0.76	10	0.07	9.82

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
C	61	15.6	15.5	12.5	2.85	0.00	Short	833.07	0.67	10	0.05	7.51
C	61	15.6	15.5	12.5	3.22	3.24	Adjacent	606.30	0.49	10	0.02	4.45
C	61	19.8	11.5	20.0	0.00	0.00	No Overhang	1143.78	1.00	10	0.09	8.62
C	61	19.8	11.5	20.0	0.00	1.06	Long	905.72	0.79	10	0.05	6.44
C	61	19.8	11.5	20.0	0.00	3.18	Long	787.65	0.69	10	0.06	8.91
C	61	19.8	11.5	20.0	0.98	2.74	Adjacent	658.85	0.58	10	0.05	8.68
C	61	19.8	11.5	20.0	1.72	0.00	Short	850.34	0.74	10	0.07	8.87
C	61	19.8	11.5	20.0	2.16	0.00	Short	951.45	0.83	10	0.07	8.25
C	61	19.8	11.5	20.0	2.65	3.13	Adjacent	555.91	0.49	10	0.04	8.50
C	61	20.5	20.0	18.5	0.00	0.00	No Overhang	1199.82	1.00	10	0.06	5.93
C	61	20.5	20.0	18.5	0.00	1.60	Long	973.90	0.81	10	0.06	7.63
C	61	20.5	20.0	18.5	0.00	3.03	Long	856.66	0.71	10	0.05	6.40
C	61	20.5	20.0	18.5	0.77	0.00	Short	1152.66	0.96	10	0.07	7.08
C	61	20.5	20.0	18.5	2.24	1.76	Adjacent	752.15	0.63	10	0.03	3.99
C	61	20.5	20.0	18.5	2.42	2.49	Adjacent	690.19	0.58	10	0.04	6.35
C	61	20.5	20.0	18.5	2.75	0.00	Short	899.99	0.75	10	0.07	9.60
C	61	24.0	18.0	10.0	0.00	0.00	No Overhang	1339.98	1.00	10	0.08	8.14
C	61	24.0	18.0	10.0	0.00	1.49	Long	1088.52	0.81	10	0.06	7.44
C	61	24.0	18.0	10.0	0.00	2.24	Long	1039.97	0.78	10	0.04	5.58
C	61	24.0	18.0	10.0	0.48	1.82	Adjacent	931.31	0.70	10	0.06	7.95
C	61	24.0	18.0	10.0	1.60	0.00	Short	1039.64	0.78	10	0.04	5.29
C	61	24.0	18.0	10.0	3.14	2.22	Adjacent	709.29	0.53	10	0.05	9.13
C	61	24.0	18.0	10.0	3.18	0.00	Short	935.29	0.70	10	0.05	6.60

Appendix 2. Averaged test results for the validation boxes.

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
B	26	11.0	8.0	5.8	0.00	0.00	No Overhang	305.42	1.00	10	0.06	5.72
B	26	11.0	8.0	5.8	0.00	0.38	Long	260.43	0.85	10	0.05	5.81
B	32	20.3	11.5	22.4	0.00	0.00	No Overhang	388.14	1.00	10	0.04	4.16
B	32	20.3	11.5	22.4	2.18	0.00	Short	311.26	0.80	10	0.07	8.17
C	32	8.8	8.0	8.0	0.00	0.00	No Overhang	435.60	1.00	10	0.07	7.49
C	32	8.8	8.0	8.0	0.00	2.06	Long	341.34	0.78	10	0.06	7.07
C	32	9.0	9.0	11.0	0.00	0.00	No Overhang	766.65	1.00	10	0.06	6.29
C	32	9.0	9.0	11.0	0.00	2.59	Long	561.88	0.73	10	0.03	4.57
C	32	10.3	5.3	7.7	0.00	0.00	No Overhang	480.65	1.00	10	0.04	4.40
C	32	10.3	5.3	7.7	0.55	0.00	Short	410.55	0.85	10	0.08	9.00
C	32	10.6	10.6	14.8	0.00	0.00	No Overhang	545.08	1.00	10	0.05	5.03
C	32	10.6	10.6	14.8	2.85	0.00	Short	367.51	0.67	10	0.06	8.27
C	32	11.0	7.3	9.5	0.00	0.00	No Overhang	428.72	1.00	10	0.07	6.70
C	32	11.0	7.3	9.5	0.41	1.42	Adjacent	265.35	0.62	10	0.04	6.13
C	32	13.8	9.3	10.3	0.00	0.00	No Overhang	483.49	1.00	10	0.06	5.93
C	32	13.8	9.3	10.3	0.99	2.52	Adjacent	256.43	0.53	10	0.04	8.30
C	32	15.0	14.0	6.0	0.00	0.00	No Overhang	1005.07	1.00	10	0.04	4.27
C	32	15.0	14.0	6.0	1.45	2.81	Adjacent	547.32	0.54	10	0.02	4.35
C	32	15.3	10.3	14.0	0.00	0.00	No Overhang	479.64	1.00	10	0.05	5.11
C	32	15.3	10.3	14.0	1.29	0.00	Short	410.02	0.85	10	0.05	5.35
C	32	15.5	11.5	15.0	0.00	0.00	No Overhang	520.72	1.00	10	0.07	7.04
C	32	15.5	11.5	15.0	3.01	0.44	Adjacent	320.79	0.62	10	0.06	10.23
C	32	18.3	12.5	9.5	0.00	0.00	No Overhang	1010.29	1.00	10	0.05	5.23
C	32	18.3	12.5	9.5	0.00	2.91	Long	684.01	0.68	10	0.03	4.82
C	40	11.8	9.0	5.4	0.00	0.00	No Overhang	574.02	1.00	10	0.07	6.84
C	40	11.8	9.0	5.4	2.53	0.00	Short	378.48	0.66	10	0.05	6.96
C	40	15.5	7.3	6.0	0.00	0.00	No Overhang	870.75	1.00	10	0.03	2.72

Flute	ECT	Length	Width	Height	Overhang Short	Overhang Long	Pivot Box Side Overhanging	Average of Compression Strength (lbf)	Y (Remaining Box Compression Strength Percentage)	Number of Tests Conducted	Standard Deviation	CoV
C	40	15.5	7.3	6.0	0.00	1.93	Long	602.12	0.69	10	0.04	5.54
C	44	10.8	7.3	10.4	0.00	0.00	No Overhang	671.84	1.00	10	0.05	4.81
C	44	10.8	7.3	10.4	0.65	0.51	Adjacent	453.19	0.67	10	0.04	6.10
C	44	11.2	10.4	7.5	0.00	0.00	No Overhang	542.34	1.00	10	0.03	2.67
C	44	11.2	10.4	7.5	2.69	1.09	Adjacent	286.41	0.53	10	0.02	3.48
C	44	12.5	11.3	4.3	0.00	0.00	No Overhang	1398.56	1.00	10	0.06	5.61
C	44	12.5	11.3	4.3	0.29	0.00	Short	1168.72	0.84	10	0.06	7.13
C	44	16.0	11.0	5.9	0.00	0.00	No Overhang	792.95	1.00	10	0.10	10.49
C	44	16.0	11.0	5.9	2.08	0.98	Adjacent	553.81	0.70	10	0.04	6.01
C	44	17.5	10.3	5.4	0.00	0.00	No Overhang	1104.46	1.00	10	0.08	8.22
C	44	17.5	10.3	5.4	2.31	0.00	Short	783.48	0.71	10	0.02	3.10