FIBRE BOX ASSOCIATION®

FBA 2019 RFP - FBA Unitization Project
FINAL PROJECT REPORT – Revised May 2021

Project Title
Influence of Pallet Pattern on Top to Bottom Compression Performance of Unitized Loads

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Abstract
Environmental factors estimate a corrugated container's ability to withstand a variety of conditions it will encounter during the distribution process. Examined during this research project was the influence of the pallet pattern on top to bottom compressive resistance for stacked corrugated containers. Two commonly used ECT board grades, 32 and 44ECT, were used to construct single wall C-flute regular slotted containers, having outside dimensions of 19.5" x 13" x 12". To force the failure location to the bottom of the unit load stack, the boxes were loaded with a plywood panel and bagged salt before undergoing a two-step conditioning cycle in line with TAPPI T402. The pallet patterns evaluated during this study were columnar aligned, columnar misaligned, interlocked, and hybrid. Unit loads were assembled stacking directly on the steel base plate of the compression tester and a fixed rate compression test was performed using a fixed upper platen. Results from this study showed that columnar aligned provided the greatest compressive resistance and the interlocked stacking arrangement yielded the lowest of the patterns evaluated. Environmental factors were calculated based on individual box compression tests performed and were compared to currently available multipliers available from the Fibre Box Association.

1. Introduction

A unit load system is the predominant means of moving packaged goods through the supply chain[1]. Traditionally, the unit load system is comprised of three fundamental factors: pallet, package, and stabilizer[2]. The package component most commonly used in conjunction with the unit load system is the corrugated container. The corrugated container must be designed and tested to fundamentally understand if it can withstand the distribution channel it will pass through. A common test used to evaluate corrugated containers is the compression test. Compression testing of corrugated containers can help establish metrics for determining how successful a package and subsequent unit load will be for traversing the supply chain. To successfully design a system, the packaging industry relies on a series of environmental factors used to relate the box compression test (BCT) to the expected performance of the unit load system in the field[3]. These environmental strength reduction factors, used as multipliers, were compiled for time under load, the humidity of the loading environment, stacking pattern, palletization, and other unitizing influences.

A variety of stacking patterns are available to select when constructing a unit load system. The pattern is often selected by what the system is looking to overcome. Columnar aligned stacking configuration provides the greatest top to bottom compression strength because it aligns all the corners of the packages. Although providing the greatest resistance for vertical top to bottom compression, the arrangement can be unstable depending on the geometric dimensions of the stacked containers. Interlocked patterns are comparably more stable than columnar aligned of the same containers, but there is a noted reduction in stacking strength due to the corners, which offer the greatest support to the container, not being in alignment[3]. The hybrid stacking pattern is a combination of columnar and interlocked. This stacking pattern looks to blend the sought after characteristics of both columnar and interlocked.

Many of the environmental factors used to predict the performance of the stacked containers are based on research data performed in the 1960s and 70s [4,5]. Since this time, containerboard and the process for converting corrugated containers have changed or been improved upon. Singh et al.[6] reported that perfectly aligned stacks of corrugated containers reported between 6-15% reduction in compression strength when compared to the individual box compression test. In the literature reviewed, the most prevalent comparison of stacked containers was between column aligned and interlocked patterns. Previous research reports[3–5,7,8] showed a 35-60% loss for corrugated containers stacked in an interlocked pallet pattern. Singh et al.[6] noted offsetting and misaligning two adjacent panels of a stack of containers could result in a reduction in compression strength of almost 60%. A study conducted by Rha[9] reported a percent reduction in compression strength based on the percentage of contact area showing that the reduction of diagonally misaligned containers could be as high as 51%. The majority of the studies reviewed used a single stack of containers (between 2 and 3 containers high), which would not necessarily represent typical stack height of a unit load. Additionally, by using a single stack of containers, the interactions between surrounding packages would not be observed which could influence the stacking behavior.

Laboratory testing is designed to provide an assessment to accurately depict field measured responses. The majority of testing research related to box compression has used empty containers to evaluate stacked containers and their performance against these environmental factors. Frank et al.[10] performed research indicating that by using loaded containers, the failure locations of laboratory-based testing more closely match that of field failures that occur to the bottom of the unit stack. Their study showed that the failure mechanism and location of empty stacked containers occur in the middle of the stack, not at the bottom as observed in field failures[10].

The objective of this project was to evaluate the environmental factor, "Pallet Pattern", and its influence on top to bottom compressive resistance of two different grades of corrugated boxes. Examined in this study were unitized corrugated boxes with the following stacking patterns: columnar aligned, columnar misaligned, interlocked, and hybrid.

2. Materials and Methods

2.1 Corrugated Containers

Two nominal corrugated board grade materials were selected for this project: 32 and 44ECT. The containers designed for this experiment were single-wall C-flute regular slotted containers (RSC) having outside dimensions of 19.5" x 13" x 12". The containers were converted by Pratt Industries and delivered to the Rochester Institute of Technology in February 2020. Upon receipt of the palletized knocked down (KD) boxes, the containers were randomized and sorted based on their nominal ECT values, either 32 or 44ECT. The randomized samples were restacked onto pallets and stored KD at ambient conditions for the duration of the experimental period. During the randomizing of the samples, the caliper of the board was measured using a digital caliper, and taking measurements along the major flap. Twenty boxes were selected and measured. Table 1 displays the physical properties measured during the preparation and randomizing of the samples.

Table 1. Physical properties of the boxes used in this study.

	32ECT	44ECT
Nominal combination (lb/msf)	32-23-35	56-23-56
Caliper (mils)	154 ± 1.9	167 ± 2.6
Length (in.)	19.5	19.5
Width (in.)	13	13
Depth (in.)	12	12

2.2 Single Box Compression (Empty Containers)

Ten samples of each grade corrugated box were selected randomly from the storage lot. The samples were erected and closed using hot melt glue to join the minor and major flaps of the container. Upon construction, the samples were subjected to a pre-conditioning and conditioning cycle as defined by TAPPI T402. After the completion of the conditioning cycle, the samples were removed individually and a compression test was performed on the container as defined by TAPPI T804.

To execute the single box compression tests, a Lansmont Compression Tester Model 122-15K (Lansmont Corporation, Monterey, CA USA) was used (Figure 1). The test samples were removed individually from the chamber and a top to bottom compression test was performed on each sample. The consistent orientation of the container was maintained throughout the testing where printed Box Manufacturer's Certificate (BMC) was on the bottom and the manufacturer's joint was facing towards the right side of the operator. The peak force and deflection at the peak were recorded for each of the samples as well as the force versus deflection curves.

The test parameters for the single box compression were as follows:

- Pre-load: 50 lb
- Fixed upper platen
- Platen rate: 0.5 in/min
- Yield: Compress to failure

Figure 1. Single box compression test

2.3 Unit Load Compression

The samples were erected and closed using hot melt glue to join the minor and major flaps of the container. Before closing, a plywood panel (18.75” x 12.5” x 0.5”) was placed in the bottom of the container and the weight, a water softener salt bag, placed onto the wood panel, referred to as a ‘loaded box’ (Figure 2). The addition of the plywood panel would aid in distributing the payload without creating unequal pressure points to the box below[10]. The simulated weight was loaded into the container such that it would not influence the sidewalls. Table 2 shows the average total container weight for the 32 and 44ECT containers. The loaded containers were placed individually into metal racks inside the conditioning chamber. Upon being placed inside the chamber, the samples were subjected to a pre-conditioning and conditioning cycle as defined by TAPPI T402. After the completion of the conditioning cycle, the samples were stacked to represent the pallet pattern being evaluated and a compression test was performed on the unit load as defined by TAPPI T804.

Figure 2. Corrugated container with internal weight

Table 2. Combined average weight of corrugated containers (box + plywood + salt bag)

	32ECT	44ECT
Weight (lb.)	44.6 ± .22	44.8 ± .28

To execute the unit load compression tests, a Lansmont Compression Tester Model 122-15K (Lansmont Corporation, Monterey, CA USA) was used (Figure 3). For each unit load test, 28 of the weight-filled containers were removed from the conditioning chamber. The boxes were assembled into one of the pallet patterns used for the study, stacking directly onto the steel base of the compression tester. To maintain consistent orientation and repeatability, the containers were stacked identically based on the location of the BMC for all unit load tests. The peak force and deflection at the peak were recorded for each of the samples as well as the force versus deflection curves.

The test parameters for the unit load compression were as follows:

- Pre-load: 220 lb (32 ECT) and 300 (44 ECT)
- Fixed upper platen
- Platen rate: 0.5 in/min
- Yield: Compress to failure

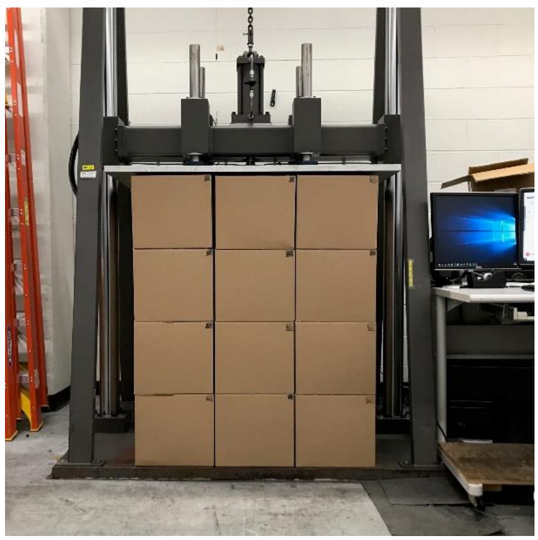

Figure 3. Unit load compression test

2.4 Stacking Orientations for Unit Load Compression

The unitized loads were constructed with seven corrugated boxes per layer, stacking four layers high. A total of 28 corrugated boxes were used to assemble each unit load. To evaluate the influence of stacking patterns, the corrugated boxes were arranged into four pallet pattern types for this study: columnar aligned, columnar misaligned, interlocked, and hybrid. Figure 4 illustrates the patterns constructed for this project. The following bulleted section describes the construction of the pallet pattern types in more detail:

- Columnar aligned
    - The corrugated boxes were aligned into columns as shown in Figure 4. To ensure the corrugated boxes were correctly columnar aligned, a series of tests were performed during the construction of the load to ensure the system was in alignment. A stacking

fixture constructed of plywood having a 90-degree angle was used as a reference to construct the bottom layers of the unit load. Careful attention was made to ensure the corners were properly aligned with each other while constructing the unit. After constructing the load, a plumb bob and level were used to ensure the stacked load was square. If any necessary changes were needed, vertical edge boards were used to adjust the load; attention was paid to safeguard against damaging the cases before testing.

- Columnar misaligned
    - The corrugated boxes were aligned into columns (Fig. 5), however, the boxes were misaligned laterally and longitudinally. For this approach, the bottom layer was constructed using the stacking fixture and the subsequent layers above were offset 0.75” diagonally in a back and forth fashion to create the misalignment for a column stacked pallet load.
- Interlocked
    - The corrugated boxes were stacked in an interlocking pattern where each layer was rotated 180 degrees from the previous layer (Fig. 4). This pattern continued until the top layer of boxes had been completed.
- Columnar and Interlocked Combined (Hybrid)
    - The corrugated boxes were stacked such that the bottom two layers were column stacked and the top two layers were interlocked. For the pallet system used for this project, the bottom two layers and the top layer will be identical, with layer 3 (from the bottom) being rotated 180 degrees as shown in Fig. 4.

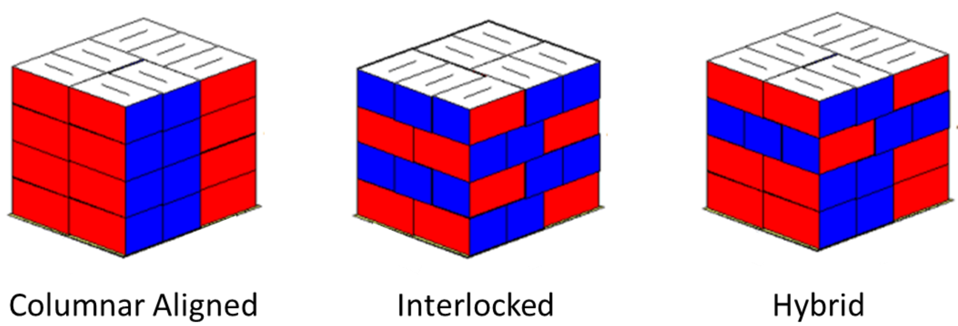

Figure 4: Pallet patterns for the experiment

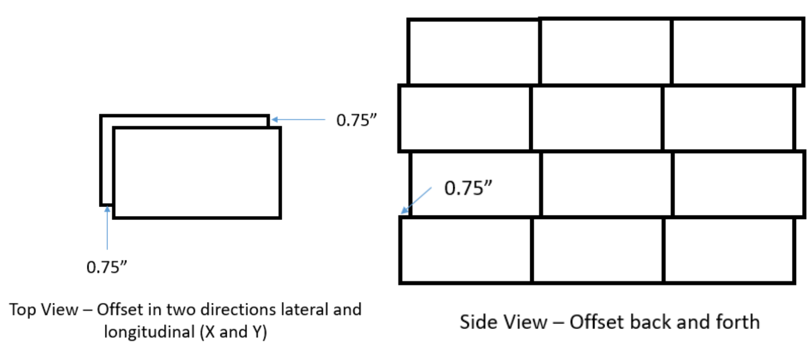

Figure 5. Example of misaligned stacking pattern offset 0.75” diagonally

2.4 Conditioning Requirements

Before testing, the test containers were closed using hot melt glue and placed inside a conditioning chamber. Following TAPPI T402, a programmable environmental chamber was used to pre-condition and condition the containers before testing. The chamber was programmed to perform a 2-step conditioning cycle: Step 1: Pre-conditioning: 30°C and 25% RH for 48 hours, Step 2: Conditioning: 23°C and 50% RH for 48 hours.

2.5 Percent Moisture Testing

A Cole-Parmer® Symmetry™ MB Halogen-Heated Moisture Balance tested the moisture content of the samples. The test samples were placed in an environmental chamber contained the test samples and the moisture content tested in different time intervals. The moisture tester records the initial weight and final weight at 105°C equilibrium condition to determine the moisture content in the samples.

Table 3 shows the averaged moisture content recorded for the individual box testing and each of the pallet patterns evaluated. The moisture contents were obtained before the start of each test and were averaged across the samples for a particular pallet pattern configuration. Although the moisture contents were lower than might be expected at equilibrium, due to their consistency across the conditions, it is not likely to affect the final comparisons.

Table 3. Average moisture content measurements for the project

Test Setup	Moisture Content (%)	
	32ECT	44ECT
Single Box	7.01	6.68
Columnar Aligned	7.02	6.73
Columnar Misaligned	7.08	6.82
Interlocked	7.01	6.70
Hybrid	7.03	6.72

3. Results and Discussion

3.1 Single Box Compression Test

The average compression strength of the 32ECT single wall container was 637.4 lb. (CV = 3.96%) with a corresponding peak deflection of 0.38 in. (CV = 6.86%). The average compression strength of the 44 ECT single wall container was 877.6 lb. (CV = 4.08%), with a corresponding peak deflection of 0.50 in. (CV = 15.8%). Table 4 displays the individual and averaged results from the compression test performed using the 10 boxes for each ECT value. Figures 6 and 7 show the force versus deflection curves for each of the samples tested. All samples compressed had a convex failure mode.

Table 4. BCT Results for 32ECT and 44ECT containers

	32 ECT		44 ECT	
Sample	**Peak Force (lb)**	**Deflection at Peak (in)**	**Peak Force (lb)**	**Deflection at Peak (in)**
1	632.6	0.35	887.6	0.45
2	662.8	0.41	901.9	0.41
3	632.5	0.39	911.0	0.58
4	644.8	0.37	864.3	0.40
5	638.5	0.39	796.4	0.43
6	576.5	0.35	907.8	0.53
7	637.8	0.35	856.2	0.53
8	636.2	0.42	915.1	0.44
9	639.6	0.40	864.7	0.59
10	672.9	0.40	871.0	0.60
Average	**637.4**	**0.38**	**877.6**	**0.50**
Range	**96.4**	**0.07**	**118.7**	**0.20**
SD	**25.2**	**0.03**	**35.8**	**0.08**
CV (%)	**3.96**	**6.86**	**4.08**	**15.80**

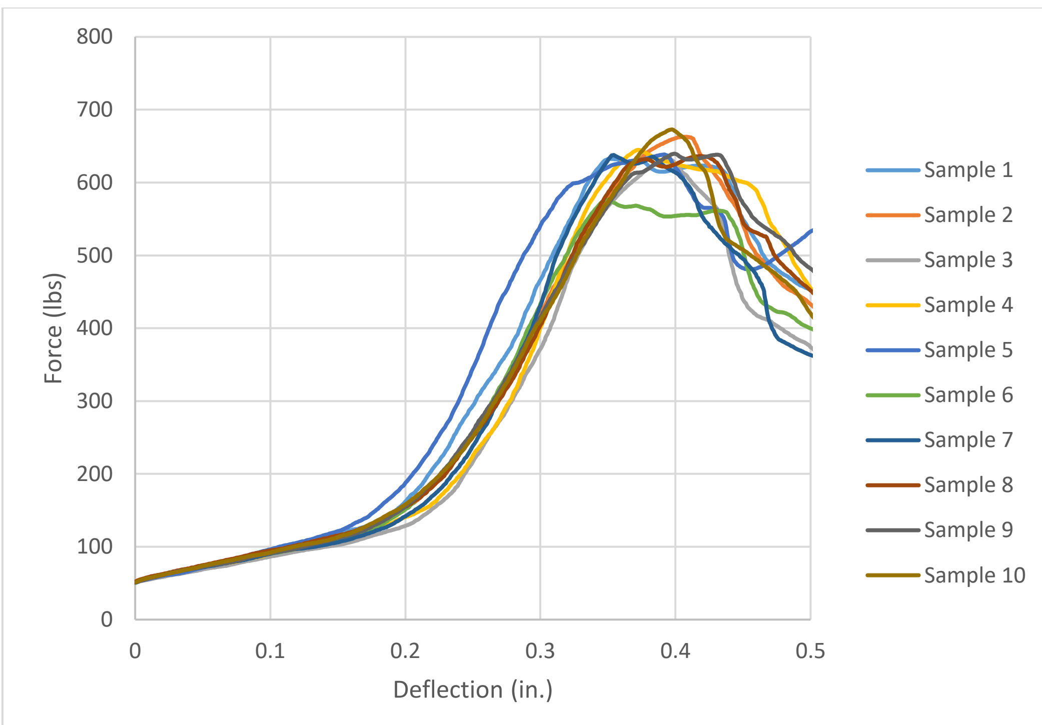

Figure 6. Compression test results for 32ECT individual containers

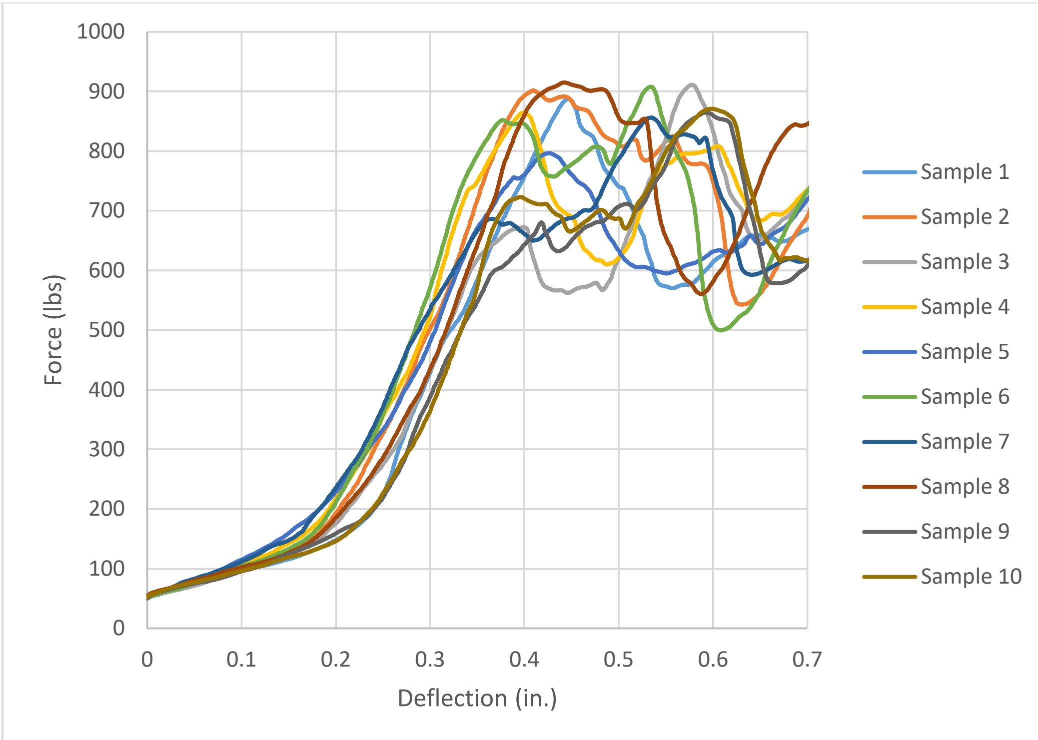

Figure 7. Compression test results for 44ECT individual containers

3.2 Unit Load Compression Test:

The unit load compression tests were executed by using randomized test blocks to account for the aging of the materials during storage for the length of the project. This allowed each pallet pattern and box grade to be evaluated over the entire duration of the project. Table 5 shows the testing pattern employed for the project. Note, due to the Covid-19 pandemic, there was a period of 10 weeks where the university was closed for on-campus research.

Table 5. Test plan used for unit load compression

				March				April				May				June				July				August			
	Test Samples			W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4
	32CA	44CA	32IL																								
	44IL	32Hy	44Hy																								
	32CA	44CA	32IL																								
	44IL	32Hy																									
	Covid-19 Shutdown																										
Testing Plan - Pallet Pattern	32CM	44CM	44Hy																								
	32CM	32IL	44CM																								
	32CA	44CM	44IL																								
	32Hy	44CA	32CM																								
	44Hy	32CM	44CA																								
	32CA	44IL	32Hy																								
	32IL	44CM	44Hy																								
	32CM	32Hy	44IL																								
	44Hy	32CA	44CM																								
	32IL	44CA																									

CA = Column Aligned
CM = Column Misaligned
IL = Interlockrd
Hy = Hybrid

3.2.1 Columnar Aligned

Table 6 displays the individual and averaged results for the vertical top to bottom compression testing performed using the columnar aligned stacking pattern. The peak force data shown in Table 6 was adjusted to include the total weight of the containers loaded with salt above the bottom layer of the stack[10]. Figures 8 and 9 display the raw data collected from the controller during the physical testing. Percent moisture was collected before the start of the testing for each of the tests using pre-cut samples stored in the chamber alongside the test samples. The initial failure location for all columnar aligned patterns tested was the bottom layer. The visible failure mode of the boxes was convex, although it is likely a mixture of convex and concave failures could be observed inside the stacked configurations given the nature that both cannot exist when situated in a side-by-side orientation as is the case with a unit load.

Table 6. Columnar aligned test results

Sample	Measured – without salt weight				Actual – with salt weight			
	32ECT		44ECT		32ECT		44ECT	
	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)
1	3013	0.84	3572	0.86	3950	0.84	4513	0.86
2	3085	0.72	4141	1.09	4022	0.72	5082	1.09
3	2784	0.77	4341	1.06	3721	0.77	5282	1.06
4	2992	0.74	3776	0.76	3929	0.74	4717	0.76
5	2986	0.72	4065	0.92	3923	0.72	5006	0.92
Average	2972	0.76	3979	0.94	3909	0.76	4920	0.94
Range	301	0.12	769	0.33	301	0.12	769	0.33
SD	112	0.05	305	0.14	112	0.05	305	0.14
CV (%)	3.78	6.62	7.66	14.70	2.87	6.62	6.19	14.70

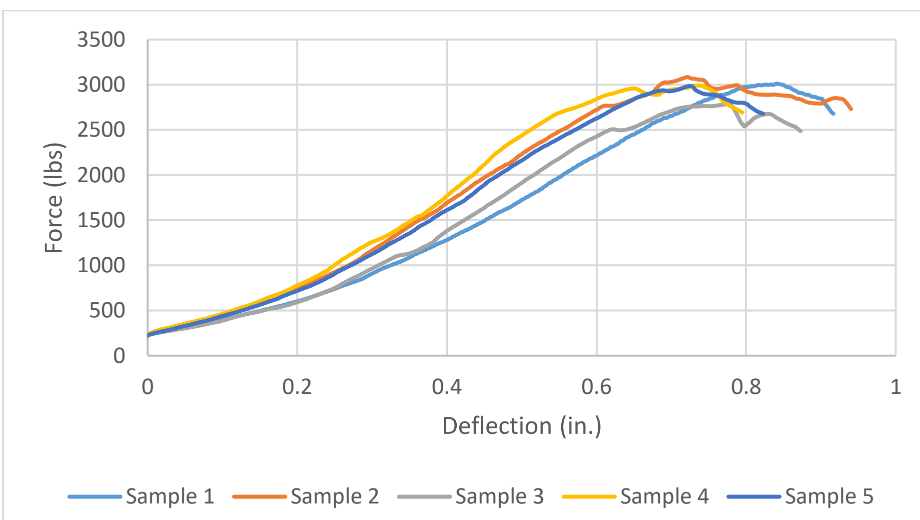

Figure 8. Columnar aligned test results – 32ECT (measured data)

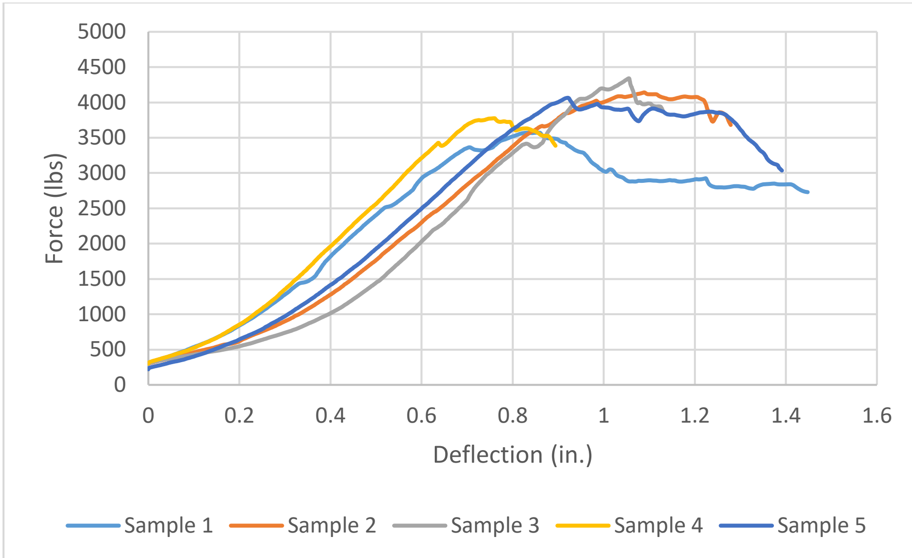

Figure 9. Columnar aligned test results – 44ECT (measured data)

3.2.2 Columnar Misaligned

Table 7 displays the individual and averaged results for the vertical top to bottom compression testing performed using the columnar misaligned stacking pattern. The peak force data shown in Table 6 was adjusted to include the total weight of the containers loaded with salt above the bottom layer of the stack[10]. Figures 10 and 11 display the raw data collected from the controller during the physical testing. Percent moisture was collected before the start of the testing for each of the tests using pre-cut samples stored in the chamber alongside the test samples. The initial failure location for all columnar misaligned patterns tested was the bottom layer. The visible failure mode of the boxes was convex, although it is likely a mixture of convex and concave failures could be observed inside the stacked configurations given the nature that both cannot exist when situated in a side-by-side orientation as is the case with a unit load.

Table 7. Columnar misaligned test results

Sample	Measured – without salt weight				Actual – with salt weight			
	32ECT		44ECT		32ECT		44ECT	
	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)
1	1496	1.55	2383	2.18	2433	1.55	3324	2.18
2	1642	1.63	2419	1.57	2579	1.63	3360	1.57
3	1639	1.74	2625	2.12	2576	1.74	3566	2.12
4	1539	1.59	2368	1.73	2476	1.59	3309	1.73
5	1445	1.54	2494	2.03	2382	1.54	3435	2.03
Average	1552	1.61	2458	1.93	2489	1.61	3399	1.93
Range	197	0.20	257	0.61	197	0.20	257	0.61
SD	87	0.08	105	0.26	87	0.08	105	0.26
CV (%)	5.62	5.03	4.29	13.69	3.50	5.03	3.10	13.69

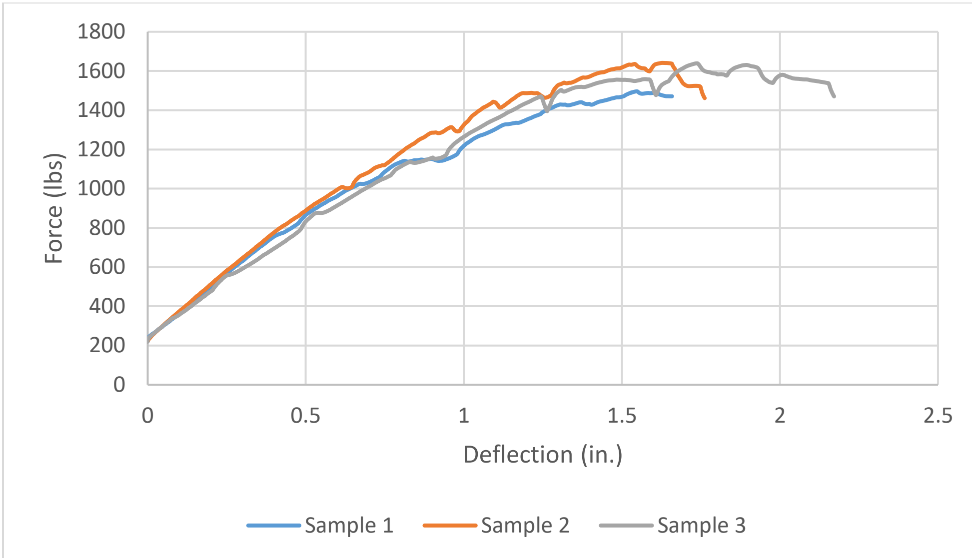

Figure 10. Columnar misaligned test results – 32ECT (measured data)

*note that the raw data collected for Samples 4 and 5 were lost due to computer failure after testing completed

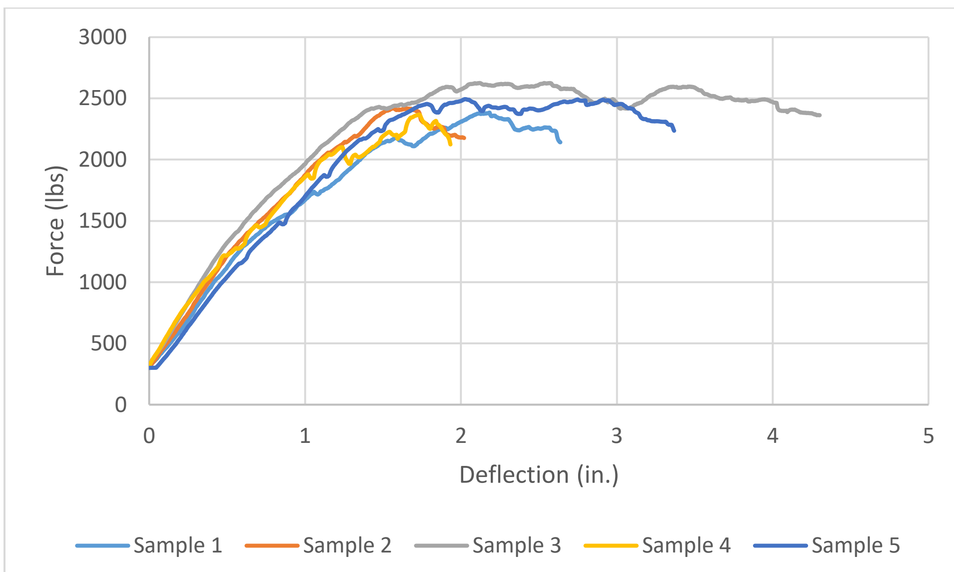

Figure 11. Columnar misaligned test results – 44ECT (measured data)

3.2.3 Interlocked Pattern

Table 8 displays the individual and averaged results for the vertical top to bottom compression testing performed using the interlocked stacking pattern. The peak force data shown in Table 6 was adjusted to include the total weight of the containers loaded with salt above the bottom layer of the stack[10]. Figures 12 and 13 display the raw data collected from the controller during the physical testing. Percent moisture was collected before the start of the testing for each of the tests using pre-cut samples stored in the chamber alongside the test samples. The average percent moisture at the start of the testing for each test was 7.01% for 32ECT and 6.70% for 44 ECT. The initial failure location for all interlocked patterns tested was the bottom layer. The visible failure mode of the boxes was convex, although it is likely a mixture of convex and concave failures could be observed inside the stacked configurations given the nature that both cannot exist when situated in a side-by-side orientation as is the case with a unit load.

Table 8. Interlocked pattern test results

Sample	Measured – without salt weight				Actual – with salt weight			
	32ECT		44ECT		32ECT		44ECT	
	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)
1	1299	0.80	2001	0.96	2236	0.80	2942	0.96
2	1468	0.79	1994	0.80	2405	0.79	2935	0.80
3	1264	0.97	1852	1.10	2201	0.97	2793	1.10
4	1429	0.65	1865	0.93	2366	0.65	2806	0.93
5	1188	0.75	1848	0.82	2125	0.75	2789	0.82
Average	1330	0.79	1912	0.92	2266	0.79	2853	0.92
Range	280	0.32	153	0.30	280	0.32	153	0.30
SD	117	0.12	78	0.12	117	0.12	78	0.12
CV (%)	8.76	14.63	4.10	13.11	5.14	14.63	2.75	13.11

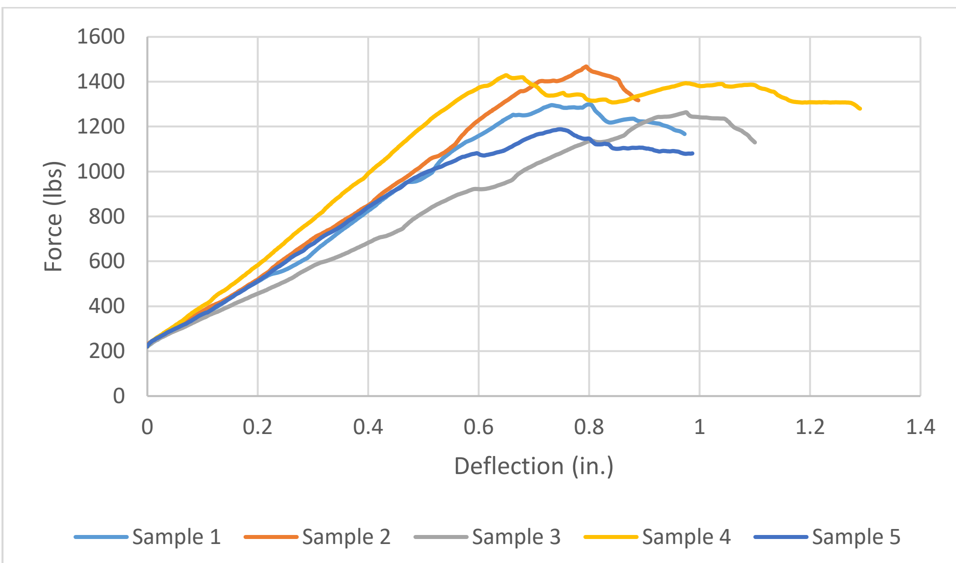

Figure 12. Interlocked pattern test results – 32ECT (measured data)

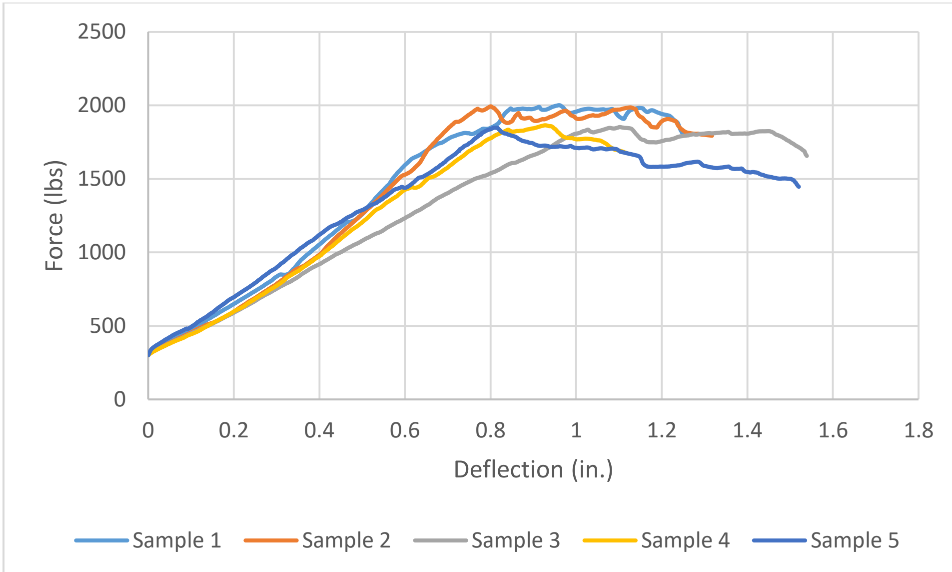

Figure 13. Interlocked pattern test results – 44ECT (measured data)

3.2.4 Hybrid Pattern

Table 9 displays the individual and averaged results for the vertical top to bottom compression testing performed using the hybrid stacking pattern The peak force data shown in Table 6 was adjusted to include the total weight of the containers loaded with salt above the bottom layer of the stack[10]. Figures 14 and 15 display the raw data collected from the controller during the physical testing. Percent moisture was collected before the start of the testing for each of the tests using pre-cut samples stored in the chamber alongside the test samples. The average percent moisture at the start of the testing for each test was 7.03% for 32ECT and 6.72% for 44 ECT. The initial failure location for all hybrid patterns tested was the second from the bottom layer. The visible failure mode of the boxes was convex, although it is likely a mixture of convex and concave failures could be observed inside the stacked configurations given the nature that both cannot exist when situated in a side-by-side orientation as is the case with a unit load.

Table 9. Hybrid pattern test results

Sample	Measured – without salt weight				Actual – with salt weight			
	32ECT		44ECT		32ECT		44ECT	
	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)	Force (lb.)	Deflection (in.)
1	1619	0.89	2663	1.26	2556	0.89	3604	1.26
2	1744	0.80	2036	1.15	2681	0.80	2977	1.15
3	1402	0.80	2114	0.75	2339	0.80	3055	0.75
4	1380	0.58	2087	0.88	2317	0.58	3028	0.88
5	1443	0.69	2108	1.05	2380	0.69	3049	1.05
Average	1518	0.75	2202	1.02	2454	0.75	3142	1.02
Range	364	0.31	627	0.51	364	0.31	627	0.51
SD	158	0.12	260	0.20	158	0.12	260	0.20
CV (%)	10.38	15.89	11.80	20.12	6.42	15.89	8.27	20.12

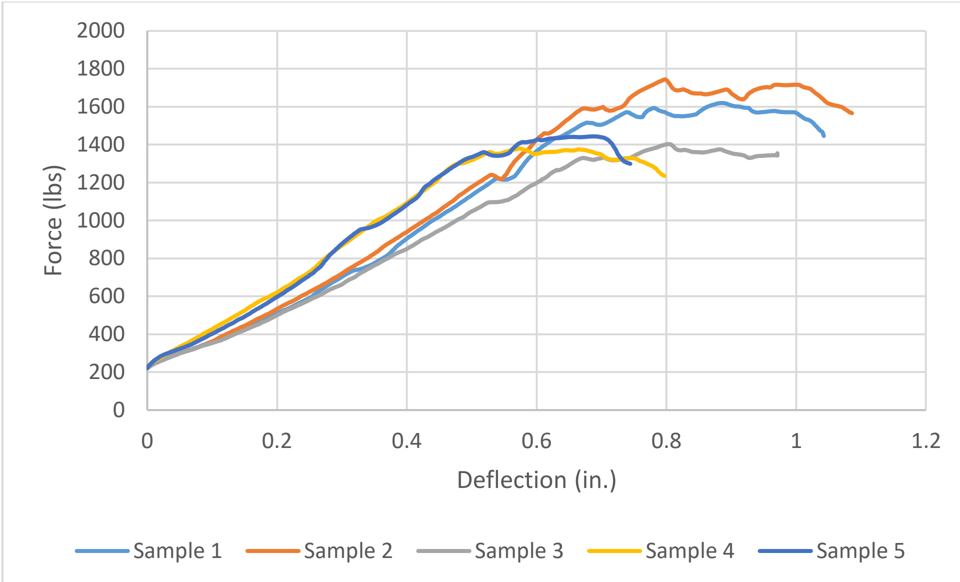

Figure 14. Hybrid pattern test results – 32ECT (measured data)

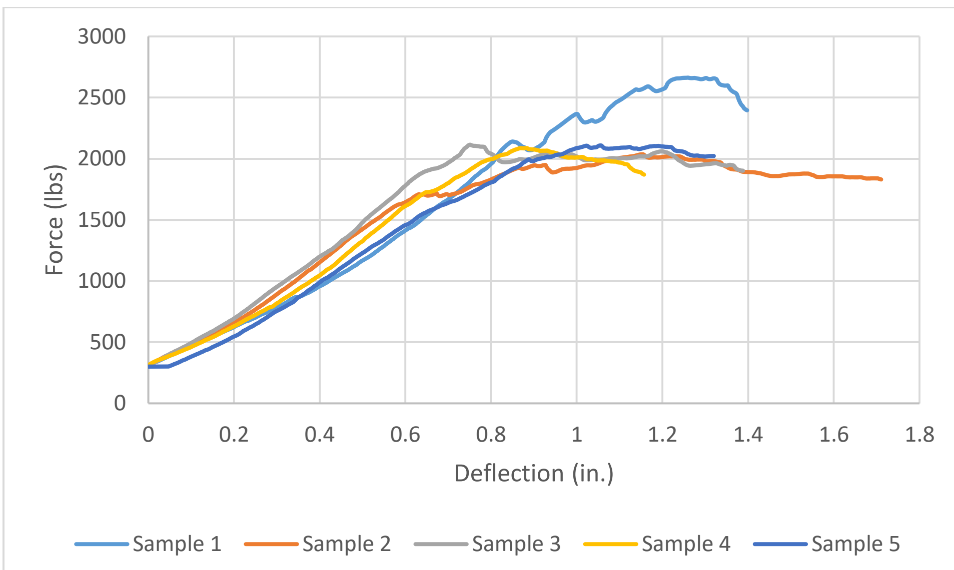

Figure 15. Hybrid pattern test results – 44ECT (measured data)

3.2.5 Summary of Pallet Pattern Test Results

Columnar Aligned

Corrugated containers support most of the load through corners, which act as a column, transferring the load from the top surface of the box to the surface below[11]. In a columnar alignment, the corners of the corrugated containers are aligned allowing for the greatest transfer of the load through the stack resulting in the greatest compressive resistance of all the stacking patterns[11]. Although offering the greatest resistance to compression, some amount of compressive loss is observed due to the stacked nature of the containers. Previous research has indicated a loss for columnar aligned containers can be between 10-12% based on the compressive resistance of the individual container test[3,10]. Results from this project report averaged individual BCT of 637.4 lb and 877.6 lb for the 32 and 44ECT containers respectively. Based on the individual BCT and the adjusted peak forces reported for columnar aligned containers, the impact of column stacking the containers for this study was between 12-20% which are in agreement with previously published research[5,6].

Figure 16 displays the overall mean adjusted compressive force for the pallet patterns evaluated during this study. The results showed that the columnar aligned stacking pattern provided the greatest resistance in compression followed by columnar misaligned, hybrid, and then interlocked. These results are in agreement with previous studies noting that columnar aligned unit loads provide higher compressive resistance than other stacking configurations[4–7,10]. For both the 32 and 44ECT, the interlocked pallet pattern provided the least amount of compressive resistance. The compressive resistance of the hybrid pattern was between the columnar misaligned and the interlocked patterns. Although the hybrid pattern did provide more compressive resistance as compared to the interlocked pattern, the improvement in resistance was not substantial. The following is a summary of the pattern on the compressive strength for each box type:

32ECT: columnar aligned > columnar misaligned > hybrid > interlocked
44ECT: columnar aligned > columnar misaligned > hybrid > interlocked

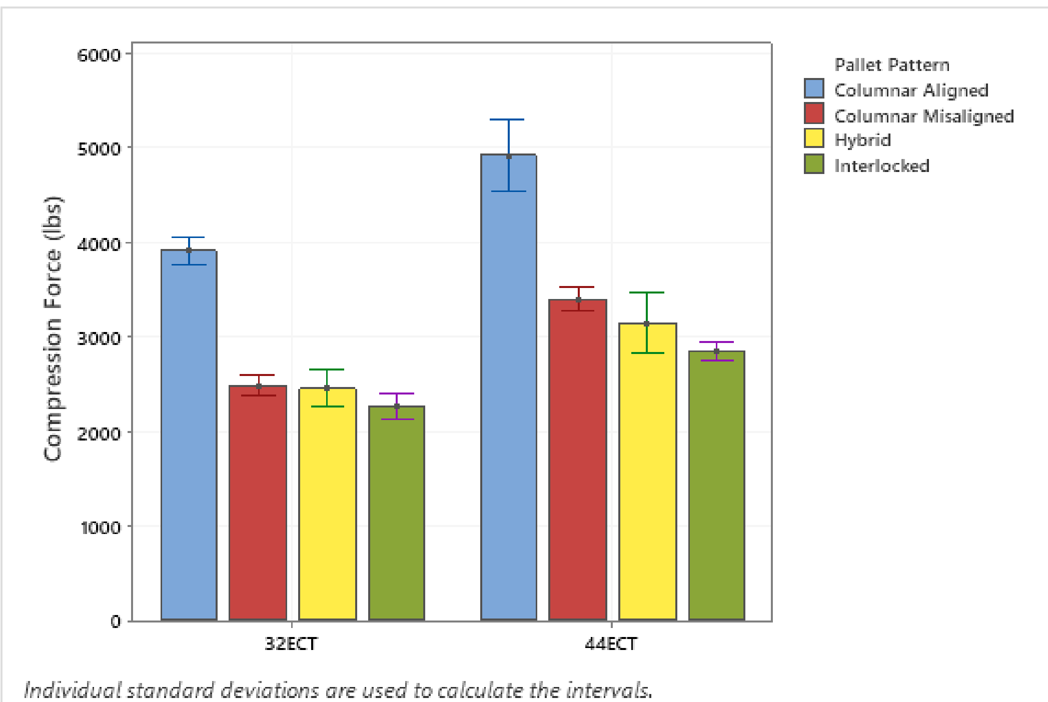

Figure 16. Mean compressive force for each box grade and pallet pattern (adjusted values)

Columnar Misaligned
Table 11 shows the compressive loss from having misaligned columnar stacked containers as compared to the single box compression results. The columnar misaligned percent loss observed from this data set is significantly greater than that reported by the Fibre Box Handbook[3,4], which states a percent loss between 10-15%. The average percent loss reported obtained through this study was 44% for 32ECT and 45% for 44ECT, which is more than twice the percent loss reported in the Fibre Box Handbook[3,4]. Not stated in the Fibre Box Handbook is the degree of the misalignment or the offset of the containers in the stack, only that the containers are misaligned. Singh et al.[6] reported percent loss of 28% and 43% for

misalignments of 0.5" and 1" respectively which corresponds with results from this study which used a 0.75" misalignment in both lateral and longitudinal directions. A study conducted by Rha[9] reported a percent reduction in compression strength based on the percentage of contact area between the test containers using a single stack of two containers. Their data showed that for boxes having 90% contact in the base area, the range of percent reduction in compression strength was between 38-51%[9]. For this study, the percent contact in the base area was 88%, and the reported average reduction was 45%, which aligns with results reported by Rha[9].

Interlocked
Table 10 shows the compressive loss from stacking containers in an interlocked pattern as compared to the single box compression results. The percent loss calculated for each of the patterns is comparable for both the 32 and 44ECT stacks of containers evaluated. The Fibre Box Handbook, along with other research reports[3–5,7,8] showed a 35-60% loss for corrugated containers stacked in an interlocked pallet pattern. The average percent loss from this study was 49-54%, which is in alignment with the currently published range.

Hybrid
The hybrid pattern is currently not a pallet pattern option listed within the Fibre Box Handbook. The researchers were unable to locate any prior published studies which presented findings associated with the hybrid pattern. Hybrid patterns are designed hoping to retain some of the compressive resistance of columnar stacking, while also being stable due to the interlocked nature of the top layers. The results from this research showed that the percent loss of the hybrid stack closely matched the behavior of the columnar misaligned. However if the misalignment was less extreme, for instance 0.25" which may be more commonly observed for stacked containers, a misaligned columnar stacked unit load would have far greater compressive resistance as compared to the hybrid pattern. The percent loss observed from this study was 45% and 49% for 32 and 44ECT respectively, which is close to the percent loss of the columnar misaligned pallet pattern from this study.

3.2.6 Environmental Factors for Pallet Patterns

Results reported from this study, suggest that the environmental factors used for pallet patterns currently used within the Fibre Box Handbook may need to be updated to reflect currently available data. Tables 11-12 display the pallet pattern and the corresponding environmental factor loss as computed through the use of the single box compression test. Figure 17 displays the overall mean adjusted compressive force for the pallet patterns compared to the single box compression test results from Section 3.1. The columnar misaligned factor within the Fibre Box Handbook is stated as a range of 0.85-0.90[3]. What is not known or published related to the columnar misaligned in the handbook is the severity of the misalignment. Results from this study, using a 0.75" offset (lateral and longitudinal) and offsetting the misalignment within the stack, resulted in a percent loss of 44-45%, representing an extreme case of misalignment. Additional testing data should be collected to determine the relationship of compression loss on misaligned containers using smaller increments to provide clarity into this factor. The interlocked pattern computed results were much better aligned with the currently reflected percent loss within the Fibre Box Handbook, reporting a percent loss of 49-54%. The hybrid pattern, which is currently not listed as a pallet pattern environmental factor, reported a percent loss of 45-49%. Based on the results of this study, Table 12 provides a single multiplier for each pattern using the mean compression loss data as reported from this study.

Table 10. Pallet pattern loss as compared to single box compression

Pallet Pattern	Force (lb)		Percent Loss (%)		Best Case	Worst Case
	32ECT	44ECT	32ECT	44ECT		
Single Layer (7 boxes)	4462	6143	-	-	-	-
Columnar Aligned	3909	4920	12	20	0.88	0.80
Hybrid	2454	3142	45	49	0.55	0.51
Interlocked	2266	2853	49	54	0.51	0.46

Table 11. Percent loss for columnar misaligned stackas compared to single box compression

Pallet Pattern	Force (lb)		Percent Loss (%)		Best Case	Worst Case
	32ECT	44ECT	32ECT	44ECT		
Single Layer (7 boxes)	4462	6143	-	-	-	-
Columnar Misaligned	2489	3399	44	45	0.56	0.55

Table 12. Single multiplier for designers by using the mean compression loss as reported from study data

Pallet Pattern	Compression Loss	Multiplier
Columnar Aligned	12 – 20%	0.84
Hybrid	45 – 49%	0.53
Interlocked	49 – 54%	0.49

*Columnar Misaligned (based on 0.75" offsetting): Compression loss of 44-45%; Multiplier 0.56

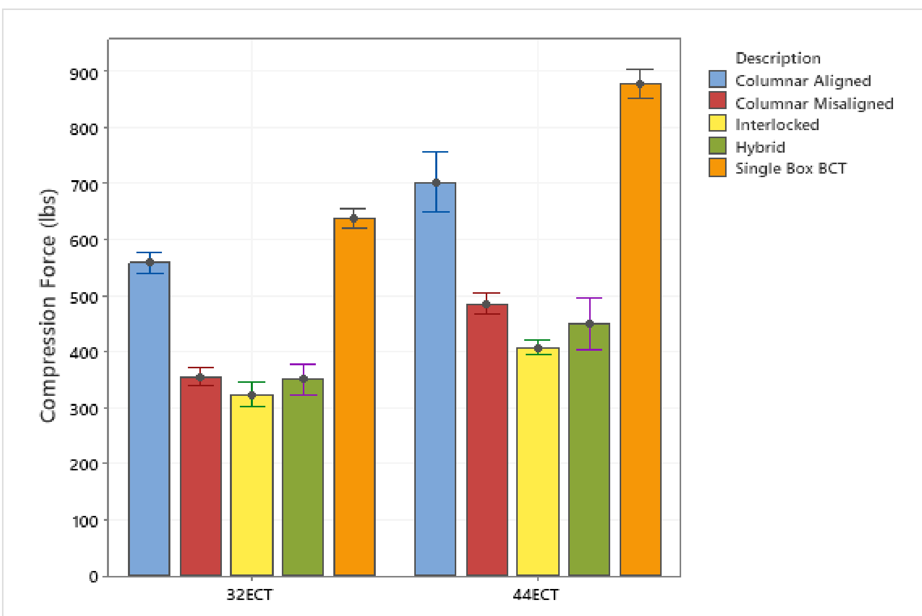

Figure 17. Mean compressive force the pallet patterns comparing single box compression BCT

4.0 Conclusions

Examined during this research project were the effects of pallet stacking patterns on the compressive resistance of unitized corrugated containers. Corrugated boxes, having outside dimensions of 19.5" x 13" x 12", were converted by Pratt Industries to produce containers with 32 and 44ECT board grades. To force the failure of the stacked containers to the bottom layer, a simulated load in the form of a salt bag was placed on a plywood board in each container before being closed and placed inside a programmable conditioning chamber. The samples were subjected to a pre-conditioning and conditioning cycle as defined by TAPPI T402. After the completion of the conditioning cycle, the samples were stacked to represent the pallet pattern being evaluated and a compression test was performed on the unit load as defined by TAPPI T804. The pallet patterns observed during this project were columnar aligned, columnar misaligned, interlocked, and hybrid. For each ECT and pallet pattern, five replications were performed and descriptive statistics were performed on the data sets.

The columnar aligned unit load had the highest compressive strength of the four pallet patterns evaluated, reporting adjusted peak forces of 3909 lb and 4920 lb for the 32 and 44ECT containers respectively. The columnar misaligned, incorporating a 0.75" offset (lateral and longitudinal), reported adjusted peak forces of 2489 lb and 3399 lb for the 32 and 44ECT containers respectively. Comparing these peak forces to the single box compression BCT, a percent loss of 44% for the 32ECT and 45% for the 44ECT containers were reported. The interlocked pattern had adjusted peak forces of 2266 lb for the 32ECT and 2853 lb for the 44ECT containers. In comparison to the single box compression BCT, a percent loss of 49% and 54% were observed for the 32 and 44ECT containers respectively. The hybrid stacking configuration reported adjusted peak forces of 2454 lb for the 32ECT and 3142 lb for the 44ECT containers. This resulted in a percent loss of 45% and 49% for the 32 and 44 ECT containers respectively as compared to the single box compression BCT.

The results created from this project may be used to update the environmental factors provided by the Fibre Box Handbook related to "Pallet Pattern". The Fibre Box Handbook provides multipliers that can be used to estimate the impact of pallet pattern configuration using the compression strength of an empty box. For columnar aligned, a multiplier of 0.84 was calculated based on the mean compression loss observed from this study. This value is currently outside the range of currently provided by the Fibre Box Handbook. Results from this study are in line with the suggested interlocked pattern, but recommends a multiplier for instances of when stacked containers are severely misaligned and provides a new option for hybrid stacking. For the interlocked pattern, this research reported a multiplier of 0.53, which is in the range of 0.40-0.60 currently used by the Fibre Box Handbook. For misalignment, which for this study evaluated an extreme case of stacking misalignment, a multiplier of 0.55 was calculated based on the mean compression loss. Currently, the Fibre Box Handbook does not include a multiplier specifically related to the hybrid pallet pattern. Therefore, based on the results of this study, a multiplier of 0.49 is proposed based on the mean compression loss.

Understanding the influence of pallet patterns is critical to designing a unit load that will successfully travel throughout the supply chain to the end-user. Pallet patterns are often selected based on the geometric limitations of the pallet (cube efficiency) or to increase the inherent stability of the load. This research reveals that the stacking configuration has a tremendous effect on the overall compression strength of the load and therefore should also be a major consideration when designing unit load systems. Being able to accurately predict the compressive strength of the load will provide the designer with the ability to determine which pallet stacking pattern is best suitable for their particular application.

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