The Influence of Package Size and Flute Type of Corrugated Boxes on Load-Bridging in Unit Loads

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Pallets have been generally designed with the assumption that the payload carried by the pallet is flexible and uniformly distributed on the pallet surface. However, packages on the pallet are acting as a series of discrete loads where the physical interaction between the packages adds stiffness to the payload. The term "load-bridging" has been used to describe this charateristics of the loads on a pallet. This load-bridging can affect the deflection of the unit-load by leading to redistribution of loads from the center of the pallet to the support; therefore, it could potentially influence the load carrying capacity of the pallet by decreasing the maximum bending moment. The purpose of this study was to investigate the influence of packaging size and flute type of corrugated boxes on the deflection of unit-loads and the redistribution of loads on the pallet when unit loads are placed in warehouse storage racks. The experimental results showed that increase in the packaging sizes tested, changed the unit-load deflection by as much as 76%. While changing the corrugated box flute type from B-flute or BC-flute to E-flute reduces the unit-load deflection by as much as 23%. The study also indicates that the effect of packaging size and corrugated board flute type on unit load deflection is the greatest for low stiffness pallets.

Keyword: Unit load, Pallet, Corrugated Box, Load Briding, Stress Distribution

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1. INTRODUCTION

Internationally, the world container trade industry moved 151 million TEUs (20-foot equivalent unit), equivalent to around 1.2 billion tons of dry goods in 2011 [1]. The goods are generally transported and stored in a unit-load form at some point in the supply chain. The unit load is defined as ‘a single item, a number of items, or bulk material which is arranged and restrained so that the load can be stored, picked up, and moved between two locations as a single mass’ [2]. A unit-load consists of loads (packages containing products) on a pallet with appropriate load stabilizers. The pallet, the most common unit-load platform, facilitates the transportation and storage of goods. While shipping pallets can be made from several materials, including metal, paper, and various plastics, wood is estimated to account for more than 90 percent of the U.S. pallet market [3]. In 2011, approximately 416 million new wood pallets were manufactured in the United States [4]. Among the various load types carried by the unit load, corrugated boxes are the most widely used packaging form for transporting goods in the United States [5]. Although there is a significant interaction between these components, the components of unit loads are designed in silos which could results in added cost, reduced safety, and considerable product damage [6].

Although, numerous studies investigated the effect of pallets on the packages [7, 8, 9, 10, 11, 12, 13, 14, 15], there is a lack of information on the effect of payload (boxes, drums, bags, etc) on the performance of the pallet. In designing the pallet, it is generally assumed that the payload is flexible and uniformly distributed on top of the pallet. However, packages on the pallet are acting as a series of discrete loads where the physical interaction between the packages adds stiffness to the payload and causes the payload to bridge across supports. This load-bridging can affect the deflection of the unit-load by redistributing load from the center of the pallet to the support and consequently decreasing the maximum bending moment experienced by the pallet.

Two early studies [16],[17] examined the influences of various unit-load characteristics on the load-bridging, and found that stacking patterns and pallet stiffness significantly affected unit-load deflection. White [18] also confirmed that the deflection of the pallets was highly dependent on the types of packages (e.g. corrugated box, sacks, and drums), stacking patterns, and load stabilizers (e.g. stretch wrap and strap) that are applied to the pallet. Yoo et al. [12] investigated the compressive stress distribution between corrugated boxes and the top surface of the pallet in a warehouse floor storage scenario and quantified the redistribution of the load based on the stiffness of the package and the stiffness of the pallet top deckboard.

Although, there has been acknowledgement of load-bridging and its general effects, we still have a limited understanding of the complexity of the interactions between the pallet and the types of payload including the effect of packaging size, flute type of corrugated boxes, and containment force of load stabilizers on pallet deflection. Lacking this knowledge, pallet design methodologies use a conservative adjustment for the different types of loads carried by the pallet.

The objective of this study was to investigate the influence of rigid package size and corrugated board flute type of corrugated boxes on deflection of unit-loads and the redistribution of loads on the pallet during warehouse rack storage.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Simulated Pallet Segments

Four types of pallets were used to determine the stiffness range of typical pallets used: 1,219 mm x 1,016 mm (48 in. x 40 in.), Grocery Manufacturers Association (GMA), wood stringer class pallet made of Southern Pine, 1,219 mm x 1,016 mm block class, perimeter, base wood pallet made of mixed hardwoods, 1,219 mm x 1,016 mm multiple use polypropylene plastic, block class pallet, 1,130 mm x 978 mm (48.5 in. x 38.5 in.) single use recycled polypropylene plastic block class pallet (Figure 1). The bending stiffnesses of the four pallets were measured by a three-point bending test using a fixed platen compression tester (Tinius Olsen). The pallets were racked across their width on two circular beams with 50 mm diameter spaced 914 mm apart. An additional circular load beam was centered on the top of the pallet and was loaded by the top platen of the compression tester. The deflection of the pallet was measured by a string potentiometer (UnitMeasure, Model P510-5-S3) at the center of the pallet. The bending stiffness of the pallets were adjusted to represent the stiffness of a 1,016 mm x 254 mm segment of the pallet (Table 1).

Based on the stiffness range provided by the investigated pallets, three 1,016 mm x 254 mm wooden boards were built to simulate the low, medium, and high stiffness range of the investigated pallets. The characteristics of these simulated pallet segments are presented in Table 1.

2.1.2. Corrugated Boxes

Regular slotted container (RSC) type corrugated boxes with three different outside dimensions (508 mm x 254 mm x 254mm, 254 mm x 254 mm x 254 mm, 127 mm x 254 mm x 254 mm) and flute types (E, B, and CB) were used for this study. The were manufactured and shipped flat by Packaging Corporation of America, Roanoke, Virginia, USA. Flat crush test according to TAPPI 825 was conducted to measure the flat crush strength and stiffness of each flute type used for this study. Table 2 shows the physical properties of the corrugated boxes.

The boxes were erected using a custom jig to ensure that each edge formed a 90° angle. Rigid oriented strand board (OSB) boxes manufactured using 13 mm thick OSB board to the exact inside dimensions of the corrugated box were placed inside of the corrugated box. The OSB boxes were filled with weights and a lid was secured to the top to seal the OSB box. The flaps of the corrugated box were sealed using hot melt adhesive. The assembled boxes were conditioned at 23 °C and 50% relative humidity for at least 72 hours according to ASTM D 4332 (2006).

2.2. Testing Methods

2.2.1. Simulated Unit-load Bending Tests using Filled Corrugated Boxes

Figure 2 shows the detailed experimental test set-up. The 1,016 mm x 254 mm simulated pallet segment was supported using two 102 mm x 102 mm I-beams with 51 mm overlap at each end leaving 914 mm free span between the beams. To measure the deflection of unit-loads, two Linear Variable Differential Transformers (LVDTs) were secured to two custom yokes, and were placed on both sides of the simulated pallet segment centrally. Three layers of corrugated boxes were placed on the simulated pallet segment. The overall weight of a unit load for the unit-load bending tests was 109 kg. One floor jack was positioned under the center of the simulated pallet segment and was used to prevent the deflection of the simulated pallet segment during loading of the corrugated boxes. A dial gauge was placed 50 mm from the center on the simulated pallet segment to ensure the simulated pallet segment was level. Following the loading of the corrugated boxes, the floor jack was slowly removed to simulate the rack support condition. The deflection of the unit-load was measured for one minute using LabView® software and the two LVDTs. Following the first test, the boxes were removed the the stack was assembled by alternating the the bottom layer two more times. Overall three replications of each test were conducted inside of the environmental chamber at 23 °C and 50% relative humidity for all tests performed.

2.2.2 Pressure Distribution Mapping

A Tekscan pressure measurement system including a pressure mat (Model 5315) was used to measure the pressure distribution of the packages on the simulated pallet segments during the bending test. The pressure mat was equilibrated using a Tekscan equilibrator (Model PB100F). The pressure mat was calibrated using a two-point calibration from 7 kpa to 21 kpa. The pressure mat system was connected to an *I-Scan®* data acquisition software program that recorded the pressure obtained from each pressure sensors (sensel) of the mat between 0-34 kpa in real-time. For the bending test, the pressure mat was placed between the simulated pallet segment and the corrugated boxes. It covered one side of the simulated pallet segment, from outer edge to center. Two images were taken during the bending test, one image of the pressure distribution at the beginning of the test and a second image after the floor jack was removed. Figures 2 shows the detailed experimental set-up.

2.3 Experimental Design and Statistical Analysis

The experimental design to analyze the effect of package geometry and flute type on unit load deflection is presented in Table 3. Two separate two-way Analysis of Variance (ANOVA) were used to analyze the effects of packaging size and flute type on the unit-load deflection using different stiffness of simulated pallet segments. Simple Main Effects tests were conducted to investigate the interactions between packaging size and simulated pallet segment stiffness and between flute type and simulated pallet segment stiffness. Post-hoc analysis was conducted using Tukey’s HSD to check the level of difference among levels of variables. A statistics software, SAS® JMP®, was used for conducting the statistical analysis.

3. RESULTS AND DISCUSSION

Table 4 shows the average unit-load deflections as a function of different types of packaging sizes and box flutes for the three simulated pallet segments. Figure 3 shows the fractional changes in the unit-load deflections as a function of the flute type, packaging size, and stiffness of simulated pallet segments. To analyze how the measured unit-load deflection results for different conditions deviate from the uniform load condition, all measured experimental values were compared to the deflection values for the uniform load condition (calculated using Equation 1).

$$\delta = \frac{5WL^4}{384EI} \qquad \text{[Equation 1]}$$

Where: δ is maximum deflection (mm), W is uniform load per unit length (107 g/mm), L is the span (914mm), E is modulus of elasticity, MOE (Low stiffness simulated pallet segment: 6,970 MPa, Medium stiffness simulated pallet segment: 5,856 MPa, High stiffness simulated pallet segment: 9,555 MPa), I is moment of inertia (Low stiffness simulated pallet segment: 4.3 cm^4, Medium and High stiffness simulated pallet segments: 14.7 cm^4)

Statistically, both packaging size and box flute significantly effects the unit-load deflection (p-value<0.0001). Statistical differences among the packaging sizes and flute types for each simulated pallet segments are denoted with capital letter(s) in Tables 4 and 5.

As the size of the packaging increased, there was a significant reduction in the deflection of the unit load. For the low stiffness simulated pallet segment, the deflection of the unit-load was reduced by 33%, 56%, and 76% compared to the uniform loading condition when 124 mm, 254 mm, and 508 mm wide boxes were used, respectively. Similar trend was observed for the medium stiffness pallet section (30%, 52%, and 70%) and high stiffness pallet section (22%, 44%, and 63%) simulated pallet segments. The results also indicated that as the stiffness of the simulated pallet segment decreases, the effect of packaging size is more prominent. Earlier studies by White et al. [8] and Collie et al. [7] reported similar findings using full scale unit loads.

Figure 4 shows the distribution of compression stresses for the three package sizes and pallet stiffnesses following the load application. As the packaging size increased, more stress was concentrated at the edges of the simulated pallet segments where the I-beams provided full support to the load. As a consequence, the effective load that causes the pallet to bend significantly decreased resulting in lower pallet deflection. Similarly, as the stiffness of the simulated pallet segments decreased, more stress was concentrated at the ends.

The difference between the average deflection of the simulated unit-loads using 127 mm x 254 mm x 254 mm packages made of BC-flute or B-flute corrugated board was not statistically significant. However, the average deflection of the simulated unit-load decreased significantly when packages were made of E-flute corrugated board. When the corrugated board used for the packages was changed from B-flute to E-flute for low, medium, and high stiffness simulated pallet segments, the unit-load deflection decreased by 23%, 19%, and 19%, respectively. The observed trend was similar to the one observed during the investigation of the effect of package size where the greatest change occurred for low stiffness pallet segments.

Figures 5 shows the distribution of compression stresses for packages made of the three different flutes of corrugated board and supported by the pallet sections of three different stiffness levels. Visually there is less stress near the center of the medium and high stiffness pallet section supporting the E flute box compared to the B and BC flute. This difference is not as clear on the low stiffness pallet section. From Table 2 it is not clear that the difference in pallet section deflection and stress distribution is due to a difference in flat crush strength or stiffness. More investigation on the effect of crease, caliper, and measurement of the pressure between the side walls of the adjacent corrugated boards are needed to fully understand the observed phenomena.

To determine the load carrying capacity of a pallet design, ISO 8611 [9] testing standard defines the failure of the pallet as the physical failure of the pallet or its components or when the deflection of the pallet exceeds 6% of the free span between the test supports. Therefore, the load carrying capacity of high stiffness pallets mainly depends on their strength while the load carrying capacity of low stiffness pallets mainly depends on their stiffness. When the load carrying capacity of a pallet is deflection limited, it is clear from this research that the size of the package and to some extent the flute selection will impact the capacity of the pallet. The extent to which package design will influence the capacity of medium to high stiffness pallets must be determined by failure tests

4. CONCLUSION

As previously stated, millions of pallets are used every day to store and move goods as unitloads. The abilities the unit-loads to be safe and efficient while using appropriate packaging and pallets lead us to study several major factors. The factors included three levels of loaded corrugated boxes with three levels of pallets to determine unit-load deflection during warehouse racking conditions. From our experiment, we have come to the following conclusions:

(1) Package design effects pallet deflection and load carrying capacity when unit loads of product are stored in warehouse storage racks with free spans.

(2). Increasing the size of packages led to a significant decrease in unit load deflection. The packaging size effect on unit load deflection was the greatest for simulated pallet segment with low stiffness. For the medium stiffness simulated pallet segment, which was comparable to a stringer class wood pallet, deflection in the unit load decreased by 30%, 52%, and 70%, when package width increased to 127 mm, 254 mm, and 508 mm boxes, respectively.

(3). Unit load deflection decreased when the flute type of corrugated boxes changed from B-flute and BC-flute to E-flute for simulated pallet segments of all stiffness levels. For the medium stiffness simulated pallet segment, which was comparable to a stringer class wood pallet, unit load deflection decreased by 19%, when B-flute or BC-flute corrugated boxes were changed to the E-flute boxes. However, there was no difference between the B-flute and BC-flute in terms of unit load deflection.

(4). The pressure decreased at the center of the simulated pallet segment and increased at the end of the simulated pallet segment as the package size increased and the simulated pallet segment stiffness decreased. This redistribution of compression stresses towards the ends of the simulated pallet segments explained the lower simulated pallet segment deflections observed when larger sizes of packages and lower stiffness of simulated pallet segments were applied. In order to avoid damaging the packaging during storage in rack systems, packaging engineers must consider the effects of changes in the pallet and packaging characteristics on the stress concentration at the pallets' edges.

(4). Pallet design methods should include the effect of package design on load redistribution

5. ACKNOWLEDGMENT

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Table 1 Description of pallets and simulated pallet segments investigated in this study.

Pallets	Dimension (LxW)	Adjusted bending stiffness
Block class wood pallet	1,219 mm x 1,016 mm	13 kg/mm
Multiple-use plastic pallet	1,219 mm x 1,016 mm	7 kg/mm
Stringer class wood pallet	1,219 mm x 1,016 mm	5 kg/mm
Single-use plastic pallet	1,130 mm x 978 mm	1 kg/mm
Simulated pallet segments	Dimension (LxW)	Bending stiffness
High stiffness (19 mm) Spruce solid wood)	1,016 mm x 254 mm	9 kg/mm
Medium stiffness (19 mm) Birch plywood	1,016 mm x 254 mm	5 kg/mm
Low stiffness (13 mm) Birch plywood)	1,016 mm x 254 mm	2 kg/mm

Table 2 Description of the filled corrugated boxes used in the load-bridging tests.

Box Size (L x W x H)	Weight per box (kg)	Flute type	Flat Crush Test		Edge Crush Test (kN/m)[1]	Caliper (mm)
			Average strength (kPa)	Average stiffness (N/mm)		
127 mm x 254 mm x 254 mm	4.5	E	549 (11%)	25.7 (19%)	5.6	
		B	292 (18%)	2.9 (37%)	5.6	
		BC	151 (9%)	0.6 (25%)	8.5	
254 mm x 254 mm x 254 mm	9	B	292 (18%)	2.9 (37%)	5.6	
504 mm x 254 mm x 254 mm	18	B	292 (18%)	2.9 (37%)	5.6	

Notes: values in parentheses are percent Coefficient of Variance values.

[1] the Edge Crush Test values are the published values by the manufacturer.

Table 3 Experimental design to investigate the effect of size and flute type of corrugated boxes on unit load deflection.

Simulated pallet segments	Box Size	E-flute	B-flute	BC-flute
High stiffness	127 mm x 254 mm x 254 mm	3 replicates	3 replicates	3 replicates
	254 mm x 254 mm x 254 mm	-	3 replicates	-
	508 mm x 254 mm x 254 mm	-	3 replicates	-
Medium stiffness	127 mm x 254 mm x 254 mm	3 replicates	3 replicates	3 replicates
	254 mm x 254 mm x 254 mm	-	3 replicates	-
	508 mm x 254 mm x 254 mm	-	3 replicates	-
Low stiffness	127 mm x 254 mm x 254 mm	3 replicates	3 replicates	3 replicates
	254 mm x 254 mm x 254 mm	-	3 replicates	-
	508 mm x 254 mm x 254 mm	-	3 replicates	-

Table 4 Average simulated unit-load deflection as a function of different packaging sizes and pallet stiffness.

Box size made of B-flute corrugated board	Pallet Stiffness											
	Low				Medium				High			
	Average deflection (mm)	COV (%)	Ratio[a]	Tukey's HSD[b]	Average deflection (mm)	COV (%)	Ratio[a]	Tukey's HSD[b]	Average deflection (mm)	COV (%)	Ratio[a]	Tukey's HSD[b]
Uniform	39.9		1		11.2		1		6.9		1	
127 mm x 254 mm x 254 mm	26.7	8	0.67	A	7.9	2	0.70	A	5.3	3	0.78	A
254 mm x 254 mm x 254 mm	17.5	1	0.44	B	5.3	0	0.48	B	3.8	4	0.56	B
508 mm x 254 mm x 254 mm	9.4	3	0.24	C	3.3	5	0.30	C	2.5	6	0.37	C

Note: (a). The ratios of the average pallet deflection of each load type to that calculated for the uniform load treatment. (b).; The average deflection values for each box sizes makred by the different letters are significantly different from each other at α=0.05

Table 5 Average simulated unit-load deflection as a function of different flute types and pallet stiffness.

Flute type for a 127 mm x 254 mm x 254 mm box	Pallet Stiffness								
	Low			Medium			High		
	Average deflection (mm)	COV (%)	Tukey's HSD[b]	Average deflection (mm)	COV (%)	Tukey's HSD[b]	Average deflection (mm)	COV (%)	Tukey's HSD[b]
B	26.7	8	a	7.9	2	a	5.3	3	a
BC	26.9	2	a	7.9	2	a	5.3	3	a
E	20.6	3	b	6.4	4	b	4.3	0	b

Note: (b).; The average deflection values for each box sizes makred by the different letters are significantly different from each other at α=0.05