Wood Pallet Performance Analysis with Palletized Drums in Distribution and Warehousing

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As an integral part of the supply chain, wooden pallets are produced in large quantities, with 849 million new and recycled wooden pallets being manufactured annually in the industry. Pallets are currently designed using a uniformly distributed load to determine the load capacity. This highly generalized approach often leads to overdesign and increased material utilization. Due to a phenomenon called load bridging, when discrete packages such as corrugated boxes or industrial drums are shipped on a pallet, the weight of the load tends to distribute unevenly. This can lead to an increased load capacity for the pallet. Industrial drums are commonly used to transport large amounts of liquids and chemicals; however, their load bridging effect has not been previously researched. The objective of this study was to investigate the effect of 55-gallon drums on the pressure distribution and deflection of stringer class wooden pallets using multiple support conditions and pallet designs. Results of the study indicated that loading pallets with drums significantly reduces the deflection of the pallet in all support conditions when compared to a uniformly distributed load. It was also observed that plastic and metal drums distributed their load to the pallets differently, which resulted in significantly different load bridging effects for each drum type.

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INTRODUCTION

When analyzing the palletized supply chain, it can be broken down into three components – packages, pallets, and the material handling system utilized (White and Hamner 2005). Each component can be modified to reduce the cost of the overall unit load and increase safety. Pallets play a crucial role in the unit load design process because they act as the interface between packages and the material handling equipment, so they affect the performance, cost, and safety of the whole unit load. There are 2.5 billion pallets in circulation in the U.S. each year (Freedonia Group 2014). Wooden pallets are the most widely used pallets in the U.S. with 94% of companies using them in their supply chains (McCrea 2016). In 2016, there were 839 million new and recycled wooden pallets constructed from 9.16 billion board feet of lumber. This was 21.8% of total wood production in the U.S. (Gerber 2020). Therefore, any changes made to pallets can have large environmental implications.

The effect of the structure of wooden pallets on the strength of corrugated boxes has been widely investigated (Baker 2016, 2017; Phanthanousy 2017; Quesenberry *et al.*

2020), and it was found that pallet deck boards and the stiffness of pallets' top decks have a major effect on the strength of corrugated boxes. This indicates that the generalized use of the uniformly distributed load for pallet load capacity does not consider specifics of the unit load and its interactions with the pallet.

Load bridging has become a large topic of discussion when trying to understand how to use wooden pallets most effectively. Load bridging was first investigated by Fagen (1982), who researched load bridging for wooden pallets carrying corrugated boxes. The phenomenon of load bridging was observed when the pallet was supported in warehouse rack support, and its deflection was recorded showing that the boxes' weight was being redistributed to the supported ends of the pallet instead of being uniformly distributed across the pallet. Understanding and being able to incorporate load bridging into the pallet design process allows designers to maximize the load that pallets can carry. Load bridging can also prevent the pallet from failing due to deflection (MH1 Committee 2016), which is when the pallet deckboards deflect to the point that pallet handling machinery such as a pallet jack or forktruck cannot be used to lift the pallet. Industry members can investigate their own palletized supply chain to find potential tactics to take advantage of load bridging by changing their pallet design or pallet material. When this finding is combined with the environmental impact and material usage of the pallet, it is evident that load bridging is a key component in creating a safer, more efficient supply chain.

After Fagan's (1982) research, load bridging continued to be heavily investigated for unit loads of corrugated boxes. In 1984, Collie researched load bridging for stringer pallets, specifically looking into how support conditions affect the way that the load is distributed. Box size was investigated by Park *et al.* (2017), Morrisette (2019), and Clayton *et al.* (2019), who all studied the effect of box size on load bridging and found that load bridging increases with increasing box size. Molina *et al.* (2018) investigated the effect of corrugated box stacking patterns on load bridging and concluded that interlocked boxes increase load bridging and decrease pallet deflection. Park *et al.* (2018) found that increasing containment force, by using stretch films, increases load bridging and reduces the deflection of the pallets. In 2021, Molina *et al.* (2021) developed a simplified finite element model to further investigate the effect of various unitization factors on the load bridging effect. Despite these extensive investigations around corrugated boxes, there is a lack of information about how other packaging types, such as drums and pails, affect load bridging and consequently the deflection of pallets. Although a limited investigation was conducted on the load bridging caused by plastic pails (Alvarez Valverde *et al.* 2021), there have been no studies that focused on the effect of drums. Understanding the effect that drums have on load bridging will allow pallet designers to design more efficient and sustainable pallets.

EXPERIMENTAL

Objectives

The main objective of this project was to investigate the effect of 55-gallon drums on the pressure distribution and deflection of stringer class, wooden pallets using multiple support conditions and pallet designs.

Additional specific objectives of the project are to:

- Investigate the pallet deflection caused by different drum materials as compared to a uniformly distributed load.

- Investigate the effect of pallet design on the level of load bridging caused by the drums.

Materials

Wood pallets

The experiment included four 48 in. x 48 in., stringer class, non-reversible pallet designs: a partial four-way, four-stringer, winged pallet (D1); a two-way, four-stringer, flush pallet (D2); a two-way, three-stringer, flush pallet with 0.5 in. top deck boards (D3); and a two-way, three-stringer, flush pallet with 0.625 in. top deck boards (D4) (Fig. 1). All solid wood lumber used to construct the pallets was kiln dried to 19% moisture content and was graded standard or better.

All of the top and bottom deck boards were 5.5 in. wide Baltic birch plywood graded at BB/BB and were either 0.5 in. or 0.625 in. thickness based on the design. Seven top and five bottom deck boards were used. All top deck boards were evenly spaced. Bottom deck boards were configured so that there were two boards used as lead deck boards while the other three were clustered towards the center of the pallet. The stringers were made from 3.5 in. x 1.5 in., standard or better grade southern yellow pine boards kiln-dried to 19% moisture content. Each deck board was attached using three 2 in. long, #7 wood screws per connection. The screw holes were pre-drilled and countersunk. Once screwed in, the remaining holes were covered with wood putty. The partial four-way pallet design had notches located 6 in. from the ends of the stringers. The notches themselves were 9 in. long, 1.5 in. deep, and had a notch radius of 0.75 in. The variations between the four investigated stringer class pallets designs are presented in Table 1.

Table 1. Specifications of the Four Investigated Stringer Class Pallets Designs

Pallet Design	Deck Board Thickness (in.)	No. of Stringers	Entry Type	Wing (in.)
D1	0.5	4	Partial 4-way	1.5
D2	0.5	4	2-way	N/A
D3	0.625	3	2-way	N/A
D4	0.5	3	2-way	N/A

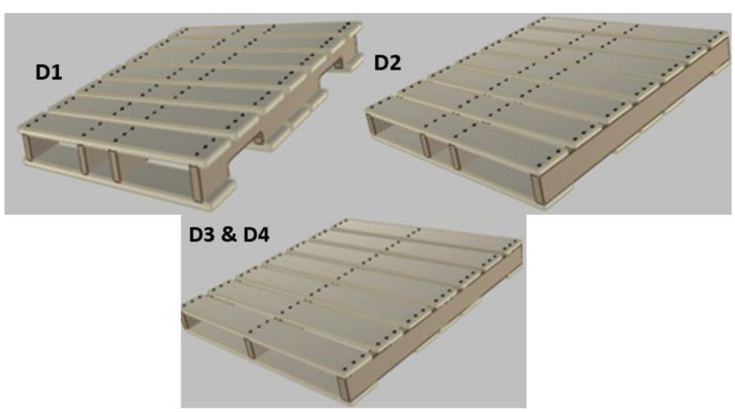

Fig. 1. Representative views of the three investigated pallet designs: D1) 4-stringer, winged, notched pallet design. D2) 4-stringer, flush pallet design. D3 & D4) 3-stringer, flush pallet design. (Images from Pallet Design System)

Drums

For this study, 55-gallon, tight-headed, steel drums (Model: ULINE S-10759) and 55-gallon, tight-headed, plastic drums (Model: ULINE S-10757) were investigated. All drums were obtained from Uline and measured before use (Table 2). The drums were filled with 55-gallons of water, which resulted in 504.5 lbs. and 489.5 lbs. filled drum weights, respectively, for the two different drum materials. Chimes are defined as the portion of the drums that have a larger diameter than the rest of the body of the drum.

Table 2. Specifications of the Investigated Drum Designs

Design	Drum Material	Top Ring Diameter	Bottom Ring Diameter	Chime Diameter	Height	Weight When Filled
D1	Metal	24 in.	24 in.	23.5 in.	34.25 in.	504.5 lb.
D2	Plastic	22 in.	N/A	21.5 in.	34.875 in.	489.5 lb.

Unit load construction

When creating the unit loads, a pressure mat (Tekscan model #7202) was sandwiched between two 0.06 in. thick polypropylene sheets. A 0.063 in. EPDM roofing rubber mat was placed on the pallet first (Fig. 2). These additional components were added to create an image that is clearer and to protect the pressure mat. The plastic sheets and the rubber mat covered the whole pallet; however, the pressure mat only covered a 27.813 in. x 24.844 in. area. The pressure mat had a 0 to 125 PSI pressure measurement range and contained 0.14 in. x 0.14 in. measurement sensels. The Tekscan equipment utilized I-scan software to record the pressure mat readings for each support condition that the unit load experienced.

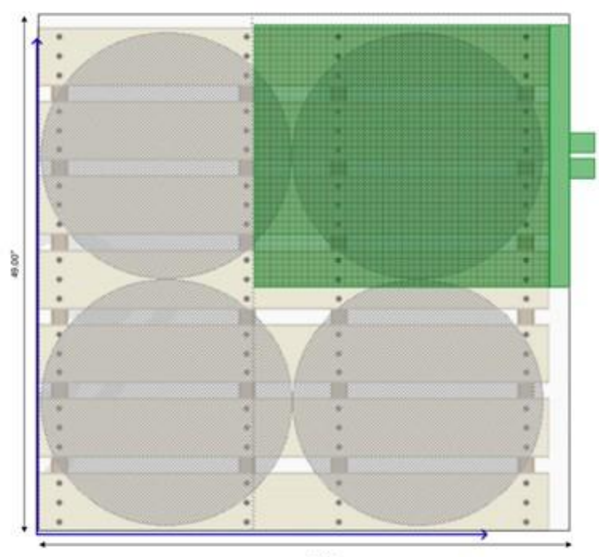

Fig. 2. Pressure mat sleeve placement on the pallet

Once the pallet was prepared with the rubber mat, the pressure mat protected between two plastic sheets were placed on the rubber and four drums were loaded onto the pallet. The drums were loaded on individually as close together as they could fit without any overhang on the stringer class pallets.

Using the results of the pressure mat measurements, the percentage of load per sensel was calculated. The data were then summed for each row to visualize the load bridging effect. This data were only used to create percentages, not exact values of data as it is modeling the pressure distribution. This calculation was then used to calculate the amount of pressure on each outer stringer of each pallet design and in every support condition.

Methods

Warehouse rack support

The pallet was supported on two 2 in. x 2 in. metal beams positioned to leave a 43 in. span under the stringer pallets. This warehouse racking support condition is meant to simulate a load beam racking system, which is the most common racking system (Mejias Rojas 2019). The load beam racking system utilizes two beams to support two edges of the pallet. The span was 43 in., so the pallet was experiencing the widest span possible while the pallet stringers are supported by the beams. The deflection of the pallet was measured using three Mitutoyo dial gauges (Mitutoyo model #4887S-19) located halfway between the supports – one at each end and one in the middle of the pallet. The pallet was tested in this support condition both across its length and width (Fig. 3).

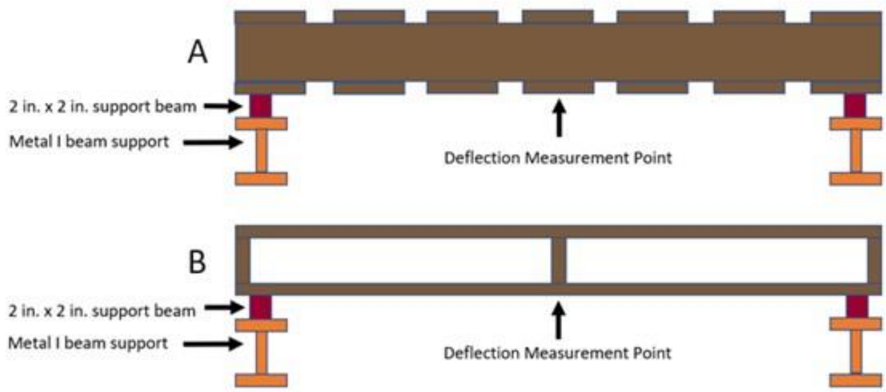

Fig. 3. A) Stringer pallet when racked across the length. B) Stringer pallet when racked across the width.

Single and double stack support

The single-stacked unit loads were placed on a level surface. Deflection measurements of the top deck boards were collected using four measurement locations at the center of the span underside each of the first four top deck boards. To simulate double stacking, a second unit load was placed on the top of the drums. The pressure between the drums and the bottom of the top pallet was measured and the deflections of the bottom deck boards were also measured in four locations. All readings were recorded (Fig. 4).

Pallet bending using a flexible airbag

The deflection of the pallet was also measured using a flexible airbag based on the guidelines of ASTM D1185 (2017). The same support conditions were investigated as were outlined in the prior section to be able to compare the uniformly distributed load to the industrial drums. A Tinius Olson compression tester equipped with four 5,000 lb. load cells was used. The deflection of the pallet was measured using string potentiometers (Standard EP Series, UniMeasure, Corvallis, Oregon, United States). The measurement locations coincided with the locations listed in prior sections. Pallets were loaded with a test load of the same weight as the four drums for the warehouse racking and the single-stack conditions; the weight of eight drums and a pallet were used for the double-stacked condition. The deflection measurements under each test load were recorded. Three replicate measurements were conducted for each pallet design.

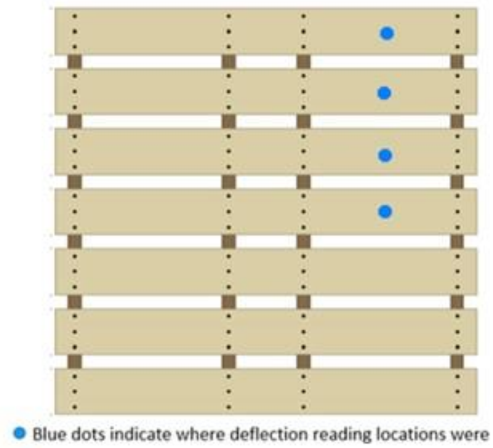

Fig. 4. Stringer pallet deflection reading locations in single and double-stack conditions

Limitations

The following limitations apply to this study:

- The results only apply to the two drum materials and styles that were investigated.
- The effect of drums was only investigated for pallet deflection; therefore, the observed reduction in deflections should not be attributed to increased load capacity.
- The effect of load stabilizers, such as a stretch wrap, was not investigated in this study; therefore, the results could significantly change if load stabilizers are used.
- Only three replicate tests were conducted for each investigated condition.

Experimental Design

The experimental design was based on two different drum materials, four stringer pallet designs, and four different support conditions (Table 3). Three repetitions were conducted for each combination of drum material and pallet design. The experiment was conducted in cycles following the same order of steps: single stack support, double-stack support, warehouse rack support across the width, and then warehouse rack support across the length. At the end of each cycle, the drums were unloaded. Deflection measurements and pressure mat readings were collected for every support condition. Each pallet experienced three cycles with each drum material. Pressure mat and deflection readings were collected two minutes after the pallet was placed into the appropriate condition.

Table 3. Summary Table of the Experimental Design

		Drum Material	
Pallet Design	**Thickness (in.)**	**Plastic Drums**	**Metal Drums**
3-Stringer, two-way, flush	0.5	3 cycles	3 cycles
	0.625	3 cycles	3 cycles
4-Stringer, two-way, flush	0.5	3 cycles	3 cycles
4-Stringer, partial four-way, winged	0.5	3 cycles	3 cycles

Statistical Model

For each of the support conditions, there were three (racking) or four (stacking) deflection measurements taken at varied locations depending on the support condition itself. The highest deflection was used to create a statistical model to further understand how pallet deflection is influenced by pallet design and drum material. The highest deflection was typically seen in the center of the pallet when placed in the racking condition.

An Analysis of Variance (ANOVA) test was conducted separately for each support condition. The deflection measurements were used as the dependent variables, while the pallet design and drum material were used as the independent variables. The analysis is described using the equation below,

$$y_{ij} = \mu + L_i + P_j + \mathrm{L}_i P_j + \varepsilon_{ij} \tag{1}$$

where y_{ij} is the pallet deflection, μ is the overall mean, L_i is the loading method with i^{th} material, P_j is the pallet design with j^{th} number, $L_i P_j$ is the interaction effect between loading method and pallet design, and ε_{ij} is the random error.

A Tukey's HSD multiple comparison analysis was also utilized with an alpha of 0.05 to further investigate the differences between pallet deflection measurements as a function of the different loading methods and pallet designs.

RESULTS AND DISCUSSION

Warehouse Rack Support Across the Length (RAL)

Deflections

The results of the pallet deflection measurements for the investigated loading methods and pallet designs are presented in Table 4. The pallet design ($p<0.0055$), loading method ($p<0.0159$), and the interaction between the two ($p<0.0062$) were all statistically significant when an ANOVA test was conducted. This demonstrates that the pallet design and the loading method both had a significant effect on the deflection of the pallet. When a Tukey HSD test was conducted, it was found that there was no difference between loading the pallet with an airbag versus metal drums. However, loading the pallet with plastic drums caused significantly greater pallet deflection than the airbag. This is due to the flexibility and the amount of contact area of the plastic drums. When the contact area was calculated for the plastic drums, it was found that 16% of the pressure is distributed through the inner ring of the drum, which is unsupported by the stringers since they do not come into contact.

The notched stringers used in the D1 pallet design could explain the greater pallet deflection as compared to the D2 pallet design that did not have any notches. Having a notch in a stringer greatly reduces its strength and stiffness, and since the pallet was being tested across its length, the stringer experienced the majority of the stresses.

The interaction between pallet design and loading method was further analyzed using a scatter plot (Fig. 5). It was found that for 4-stringer pallets, the plastic drums caused more pallet deflection than the airbag; meanwhile, for the 3-stringer pallets, the trend was the opposite. This could be due to the locations of the stringers themselves and the role that they play in the load bridging effect.

Table 4. Summary Table of Average Pallet Deflections for the Investigated Stringer Class Pallet Designs and Drum Materials Using Warehouse Rack Support Across the Length

Loading Method	Pallet Deflection (in.)							
	4-Stringer				3-Stringer, Two-way, Flush			
	Winged, Notched, 0.5 in. deck board thickness (D1)		Flush, 0.5 in. deck board thickness (D2)		0.625 in. deck board thickness (D3)		0.5 in. deck board thickness (D4)	
Airbag	0.191 (2%)		0.163 (2%)		0.165 (<1%)		0.183 (1%)	
Plastic Drum	0.236 (10%)	+24%	0.214 (4%)	+31%	0.163 (4%)	-1%	0.160 (2%)	-13%
Metal Drum	0.189 (13%)	-1%	0.171 (7%)	+5%	0.181 (7%)	-10%	0.163 (6%)	-11%

Notes: Values in parentheses are Coefficient of Variance values.

The deflections under the two drum materials were compared to the deflection caused by the airbag.

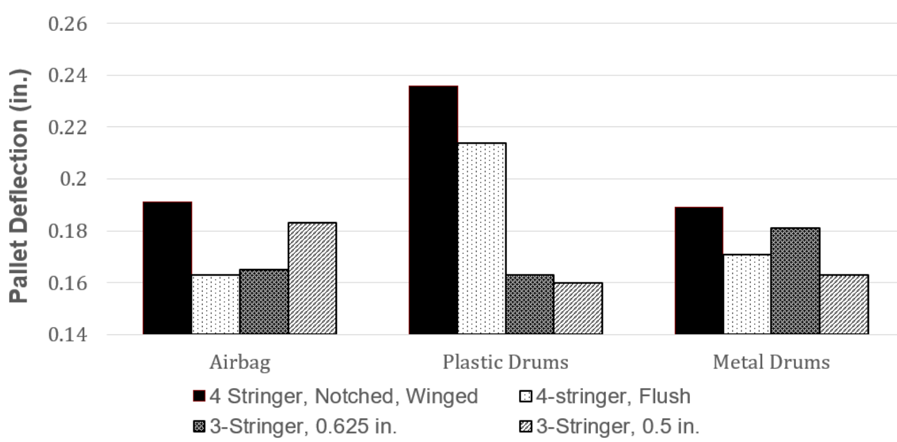

Fig. 5. Effect of loading method on the deflection of the pallet as a function of pallet design using the racked across the length support condition for stringer class pallets

Pressure mat readings

Figure 6 displays the placement of the drums on the pallets with the pressure mat distribution overlaid. The metal drums transferred their pressure through their chimes, which created a solid ring of pressure distribution. Meanwhile, due to the shape of the bottom of the plastic drum, the pressure was distributed to the pallet in a smaller circle farther away from the stringers. Due to their flexibility, the middle sections of the bottoms of the plastic drums also touched the pallets' top deck boards, creating a more even pressure distribution compared to the metal drums. The pressure distribution was further analyzed for each of the individual pallet designs (Figs. 7 to 8). It was found that the plastic drums transferred a small amount of pressure on the outer stringer ranging from 0 to 9%. Meanwhile, the metal drums had a much higher amount of pressure on the outer stringer ranging from 20 to 38%. For the metal drums, the pressure was concentrated on the stringers of the pallet, since they are the components that take on most of the load due to the rigidness of the drum material (Fig. 7). For the plastic drums, the pressure concentrated around the handles of the drums instead of concentrating around the stringers (Fig. 8).

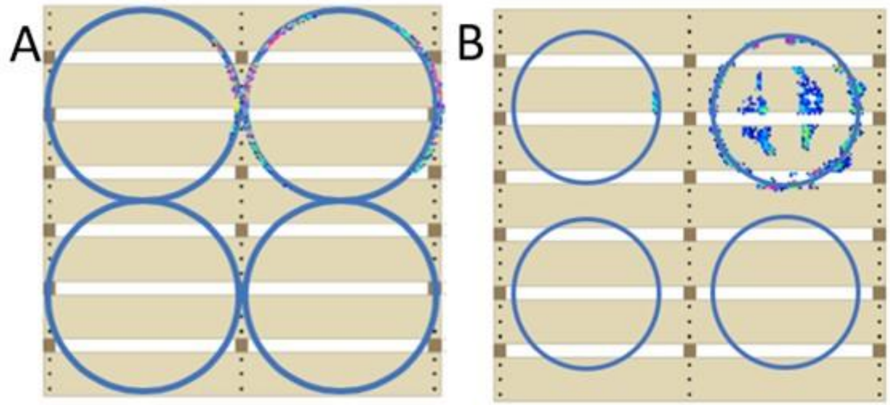

Fig. 6. Pressure distribution on pallets carrying metal drums (A) and plastic drums (B) on the 3-stringer pallet with 0.625 in. thick top deck boards (D3) during a warehouse rack support across the length

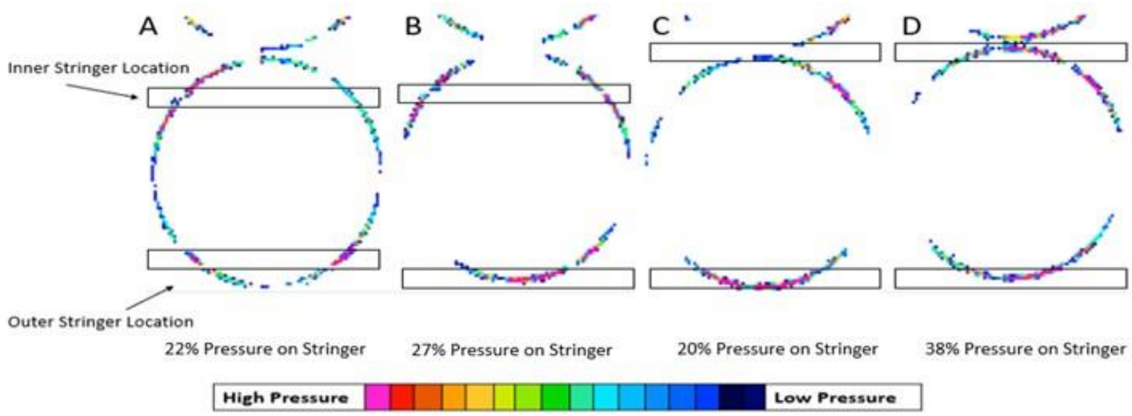

Fig. 7. Pressure distribution on stringer pallets carrying metal drums using warehouse rack support across the length. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, and D) D4 pallet design

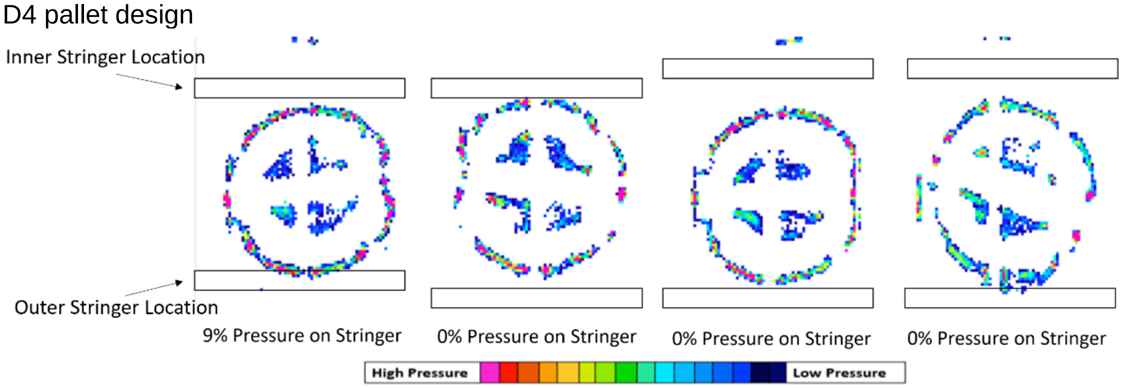

Fig. 8. Pressure distribution on stringer pallets carrying plastic drums using warehouse rack support across the length. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, and D) D4 pallet design

Warehouse Rack Support Across the Width (RAW)

Deflections

The results of the pallet deflection measurements for the investigated loading methods are presented in Table 5. The loading method (p<0.0001) and the interaction between the loading method and pallet design (p<0.0038) were both shown to be significant (alpha = 0.05). The pallet design was not significant (p<0.0530), indicating that the bending performance of the different pallet designs were not statistically different from each other. When a Tukey HSD multiple comparison test was conducted for the three different loading methods, it was found that the they were all statistically different from each other. The airbag loading produced the highest deflection. Meanwhile, the plastic and metal drum loading caused a 30 to 52% and 52 to 74% reduction in pallet deflection, respectively, compared to the airbag. The deflections indicate that there is a trend where the less stiff pallet experiences a higher reduction in deflection. This was previously seen in Park *et al.* (2017) and in Molina *et al.* (2018).

Table 5. Summary Table of Average Pallet Deflections for the Investigated Stringer Class Pallet Designs and Drum Materials Using Warehouse Rack Support across the Width

Loading Method	Pallet Deflection (in.)							
	4-Stringer				3-Stringer, Two-way, Flush			
	Winged, Notched, 0.5 in. deck board thickness (D1)		Flush, 0.5 in. deck board thickness (D2)		0.625 in. deck board thickness (D3)		0.5 in. deck board thickness (D4)	
Airbag	0.825 (<1%)		1.09 (8%)		0.764 (2%)		0.979 (<1%)	
Plastic Drum	0.467 (3%)	-43%	0.520 (2%)	-52%	0.533 (2%)	-30%	0.6 (<1%)	-39%
Metal Drum	0.272 (5%)	-67%	0.279 (3%)	-74%	0.368 (4%)	552%	0.362 (1%)	-63%

Notes: Values in parentheses are Coefficient of Variance values.

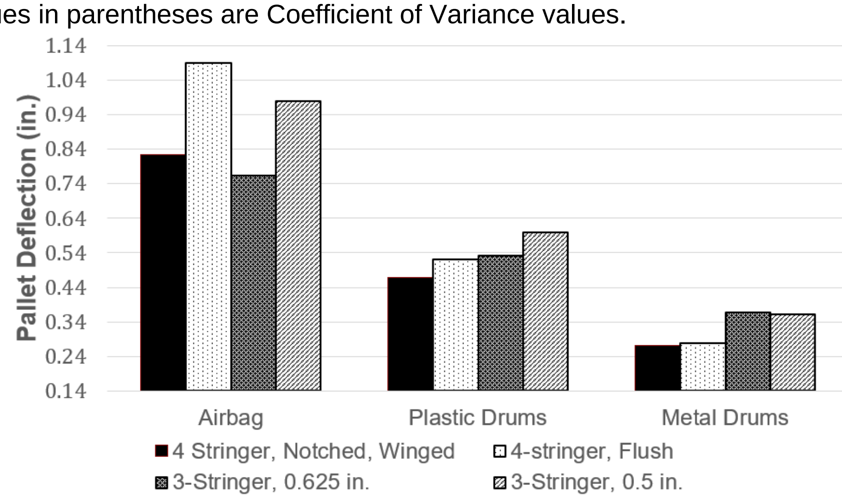

Fig. 9. Effect of loading method on the deflection of the pallet as a function of pallet design using the warehouse rack support across the width condition for stringer class pallets

The deflections of the two drum materials were compared to the deflection caused by the airbag. When the interactions between the pallet designs and the loading methods were further investigated, it was found that the RAW loading from the plastic drums produced a significantly greater effect for the 4-stringer, flush pallet (D2) than the other designs (Fig. 9). This result is similar to the one that was observed for the RAL support condition, where the plastic drum had a statistically different effect on the 4-stringer designs than on the 3-stringer designs.

Pressure mat readings

For both drum materials, more pressure was concentrated on the outer stringers (Figs. 10 and 11); this explains the much greater reduction in pallet deflection compared to RAL support. Contrary to the warehouse racking across the length condition, the pallets supporting plastic drums experienced more uneven pressure distribution which was most likely due to the more extensive bending of the pallet across the width (Fig. 11).

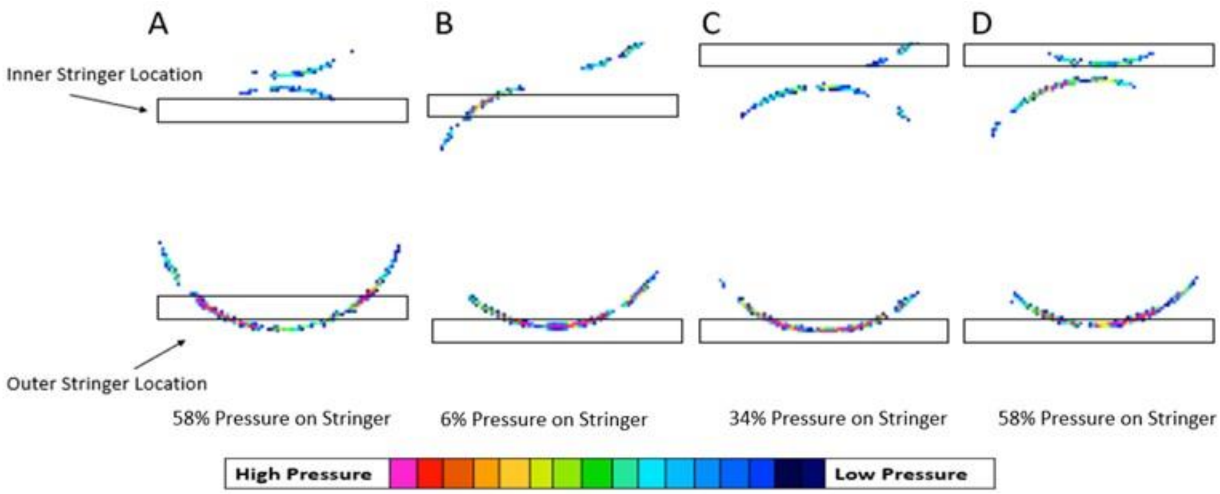

Fig. 10. Pressure distribution on stringer pallets carrying metal drums using warehouse rack support across the width. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

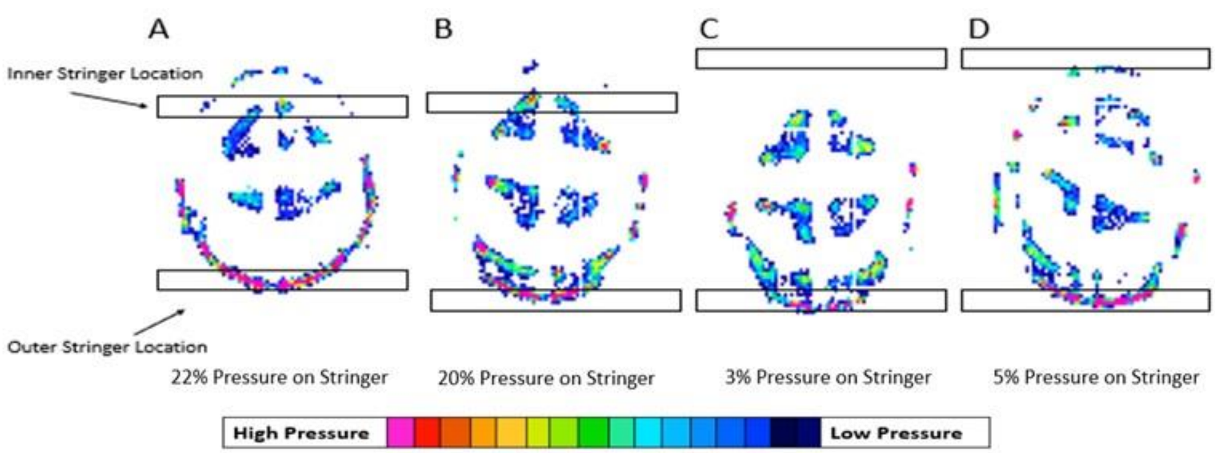

Fig. 11. Pressure distribution on stringer pallets carrying plastic drums using warehouse rack support across the width. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

When comparing the percentages of pressure on the outer stringers for the metal drums, it was seen that the pressure on the outer stringer was lowest for the 4-stringer, flush pallet than for the other 4-stringer, winged pallet design. The span between the stringers is different for each design. The span of the 4-stringer, flush pallet causes the outer stringer to be further outward and so decreases the amount of contact that is made with the metal drum when compared to the 4-stringer, winged pallet. This effect is not present in the plastic drums due to the flexibility of the materials and their ability to shift their weight easily onto the outer stringers. When comparing the metal drums to the plastic drums there was a 31 to 53% increase in pressure being distributed to the end of the pallet.

Single and Double Stack Support

Deflections

The results of the pallet deflection measurements for the investigated drum and pallet designs and the results of the airbag testing are presented in Table 6 for the single stack condition and Table 7 for the double stack condition. For both the single stack and double stack conditions, the pallet design, loading method, and the interactions between the two were all statistically significant ($p<.0001$).

When a Tukey HSD analysis was conducted for the single stack condition, only the three-stringer pallet design with the thinner deck boards (D4) was statistically different than the others due to its higher deflection. Meanwhile, the differences between pallet designs increased during the double-stack support condition. For this condition, most pallet designs were shown to be statistically different except for the D2 pallet design that was not statistically different from the D1 and D3 pallet designs. This difference between the single and double stack conditions illustrates that the pallet design becomes more crucial when there is an increase in the weight of the load placed on it.

When the Tukey HSD analysis was conducted for the loading methods in the single stack condition, it was shown that the airbag and plastic drum had the same effect on pallet deflection, while the metal drum resulted in a significantly lower pallet deflection. In the double-stack support condition, each loading method resulted in significantly different pallet deflections.

The deflection of the pallet decreased by 51 to 83% for the single stack support and 61 to 85% for the double stack support when the pallet was loaded with metal drums instead of the airbag. This was the most change for the investigated support conditions.

When the interaction between the pallet design and loading methods was further investigated, it was found that the loading method has a different effect on 3- and 4-stringer pallets (Figs. 12 and 13). The pallets in the single stack condition, loaded with metal drums, displayed the largest overall reduction (83%) on the 4-stringer pallet designs, especially for the pallet design with wings (D1), where the stringers were directly under the metal drums. The 3-stringer pallet designs experienced greater deflection when loaded with plastic drums compared to the airbag. The explanation for this phenomenon could be due to the plastic drum bottom design; plastic drums apply a more concentrated load to the middle of the deck than the metal drums.

Similar trends were observed while the airbag distributed the load more evenly due to the increase in contact area when compared for the double-stacked support. However, the effect of the pressure concentration observed in the middle of the bottom of the plastic drums, when supported on a 3-stringer pallet, decreased. The likely explanation for this change is that the extra weight during double stacking is most likely transferred down on the sidewalls, while a high percentage of the load is transferred to the deck boards through the bending of the middle section of the bottom of the drum.

The high levels of coefficients of variance are due to the measurement apparatus, which has a degree of human error and due to the overall amount of deflection. The racking conditions experienced higher levels of deflection, while the stacking supports experienced differences that fall within thousandths of an inch.

Table 7. Summary Table of Average Pallet Deflection for the Investigated Stringer Class Pallet Designs and Drum Material Using Single Stack Support Condition

Loading Method	Pallet Deflection (in.)							
	4-Stringer				3-Stringer, Two-way, Flush			
	Winged, Notched, 0.5 in. deck board thickness (D1)		Flush, 0.5 in. deck board thickness (D2)		0.625 in. deck board thickness (D3)		0.5 in. deck board thickness (D4)	
Airbag	0.104 (2%)		0.1 (4%)		0.078 (2%)		0.133 (8%)	
Plastic Drum	0.062 (9%)	-40%	0.097 (2%)	332%	0.104 (3%)	+33%	0.156 (2%)	+17%
Metal Drum	0.018 (12%)	-83%	0.026 (17%)	-74%	0.038 (16%)	-51%	0.023 (23%)	-83%

Notes: Values in parentheses are Coefficient of Variance values.

The deflections of the two drum materials were compared to the deflection caused by the airbag.

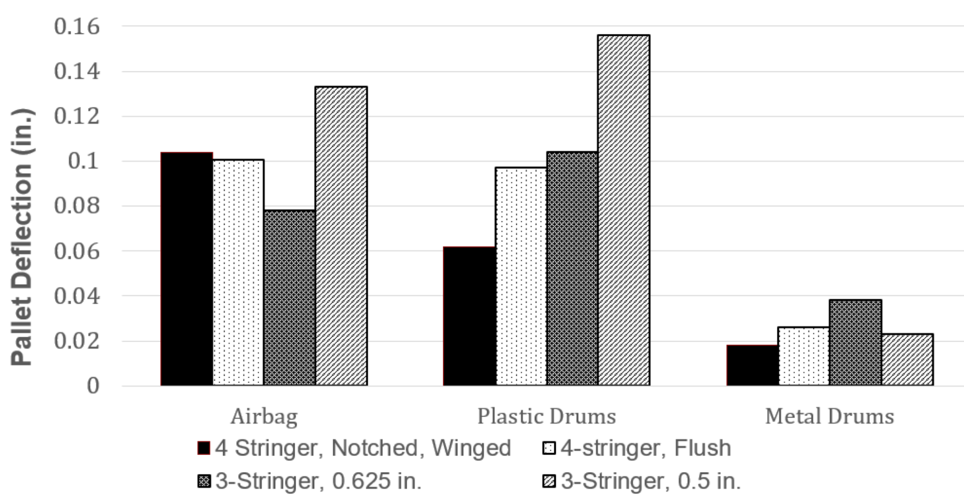

Fig. 12. Effect of loading method on the deflection of the pallet as a function of pallet design using the single stack support condition for stringer class pallets

The deflections of the two drum materials were compared to the deflection caused by the airbag.

Table 8. Summary Table of Average Pallet Deflection for the Investigated Stringer Class Pallet Designs and Drum Material Using a Double Stack Support Condition

Loading Method	Pallet Deflection (in.)							
	4-stringer				3-stringer, two-way, flush			
	Winged, notched, 0.5 in. deck board thickness (D1)		Flush, 0.5 in. deck board thickness (D2)		0.625 in. deck board thickness (D3)		0.5 in. deck board thickness (D4)	
Airbag	0.142 (16%)		0.159 (2%)		0.142 (1%)		0.247 (3%)	
Plastic Drum	0.085 (6%)	-40%	0.108 (12%)	-32%	0.126 (11%)	-11%	0.264 (2%)	+7%
Metal Drum	0.034 (28%)	-76%	0.055 (4%)	-65%	0.055 (45%)	-61%	0.035 (10%)	-85%

Notes: Values in parentheses are Coefficients of Variance values.

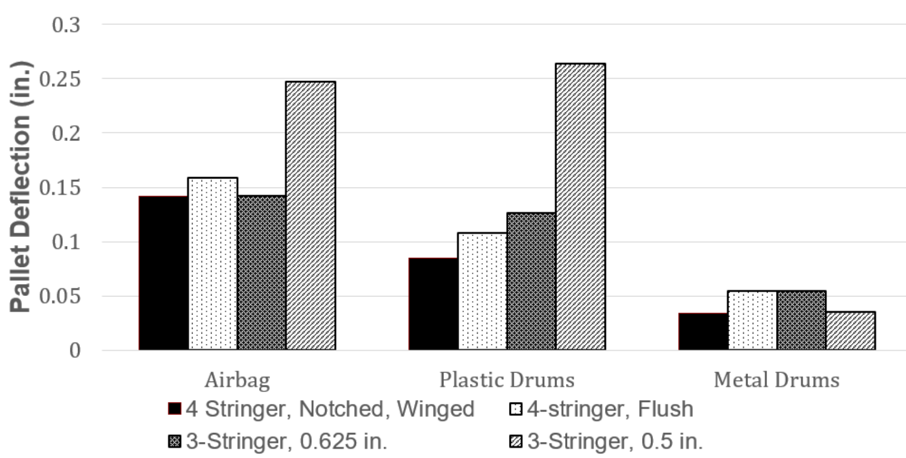

Fig. 13. Effect of loading method on the deflection of the pallet as a function of pallet design using the double-stack support condition for stringer class pallets.

Pressure mat readings

For the metal drum pressure mat readings, the main difference between the pallet designs for both the single and double stack support conditions is the amount of contact that the drum chimes made with the pallet; the contact area increases with pallet stiffness (Figs. 14 and 15). There was an increase (1 to 4%) in pressure on the stringer when comparing single stacked to double-stacked conditions due to the weight of the second unit load.

The plastic drums showed consistent pressure over the different pallet designs, but in the double-stack condition, it was clear (Figs. 17-B and 17-D) that the plastic drums can potentially flex with the pallet itself due to the additional contact that these drums have with the pallet. However, the pressure is still focused on the pallet stringers and drum handles. There is an increase in the pressure being distributed on the stringers ranging from 1 to 7% when the second unit load is added.

When the plastic drums were analyzed in the single stack condition, it was found that 19% of the pressure was concentrated in the inner area of the bottom of the plastic drum and 81% of the pressure was distributed around the outer ring of the bottom of the plastic drum. When the plastic drums were double stacked, this distribution changes due to the weight of the second unit load mainly transferring pressure down the sidewalls of the drum. This is evident when comparing the amount of pressure on the inner and outer rings of the bottom of the plastic drum. When they were double stacked, 9% of the pressure was distributed towards the inner ring of the plastic drum, and 91% was focused on the outer ring of the drum. When going from the single stack to the double stack support condition there was a 31% reduction in pressure being distributed to the inner ring of the drum and there was a 46% increase in pressure distributed to the outer ring.

For metal drums, the same behavior was not observed because of the rigidity of the bottom of the drum. The metal drums only distribute their pressure through the chime since that is the only portion of the drum that comes into contact with the pallet, unlike the plastic drums that have both an inner and outer ring that makes contact. This material difference produces a ~20% reduction in the load being distributed to the outer stringer when comparing the metal drums to the plastic drums.

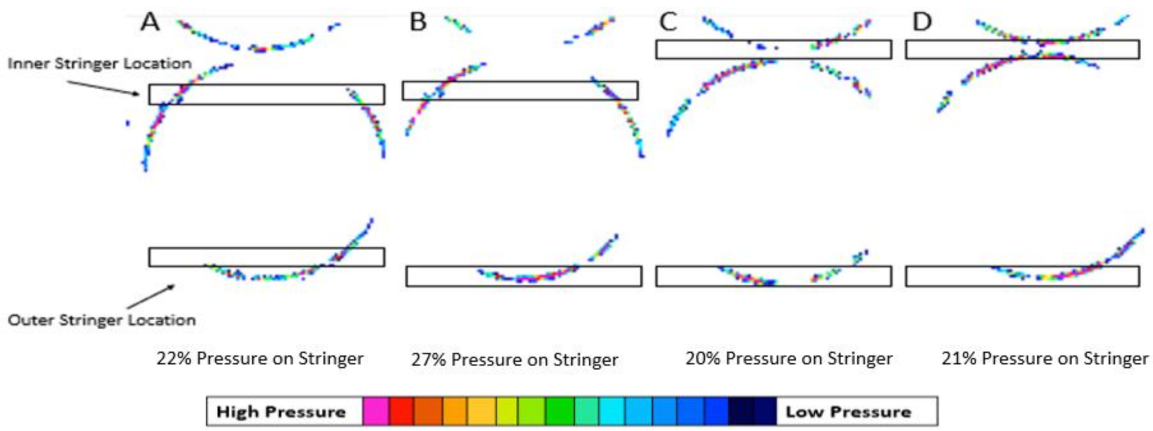

Fig. 14. Pressure distribution on stringer pallets carrying metal drums using a single stack support condition. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

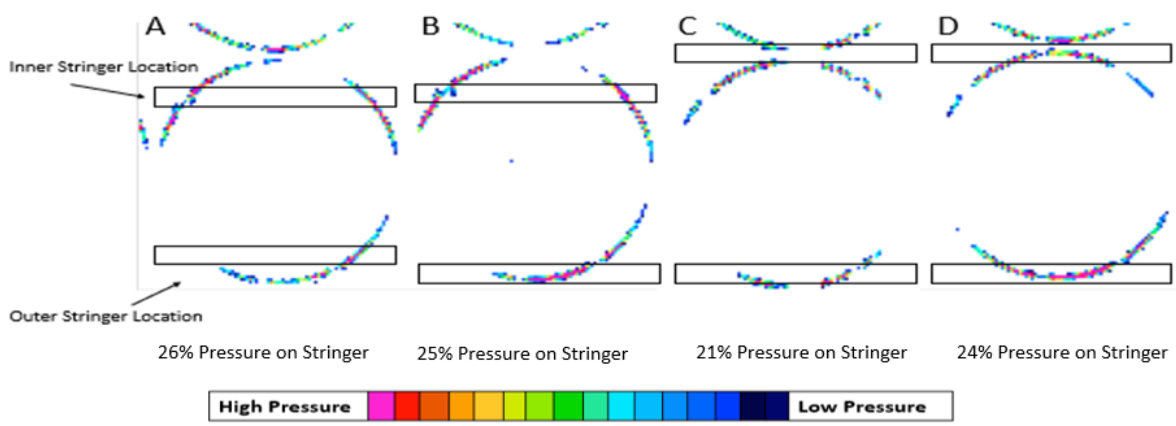

Fig. 15. Pressure distribution on stringer pallets carrying metal drums using a double stack support condition. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

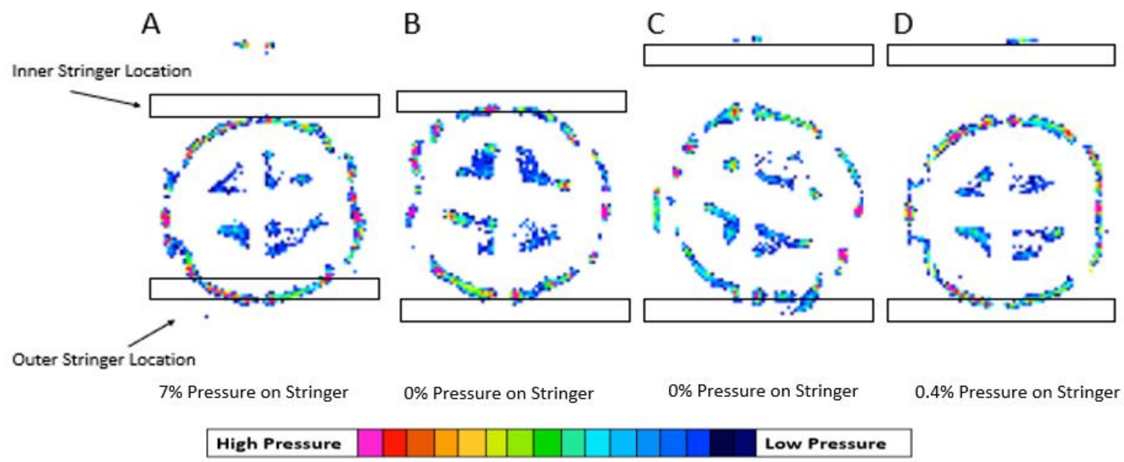

Fig. 16. Pressure distribution on stringer pallets carrying plastic drums using a single stack support condition. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

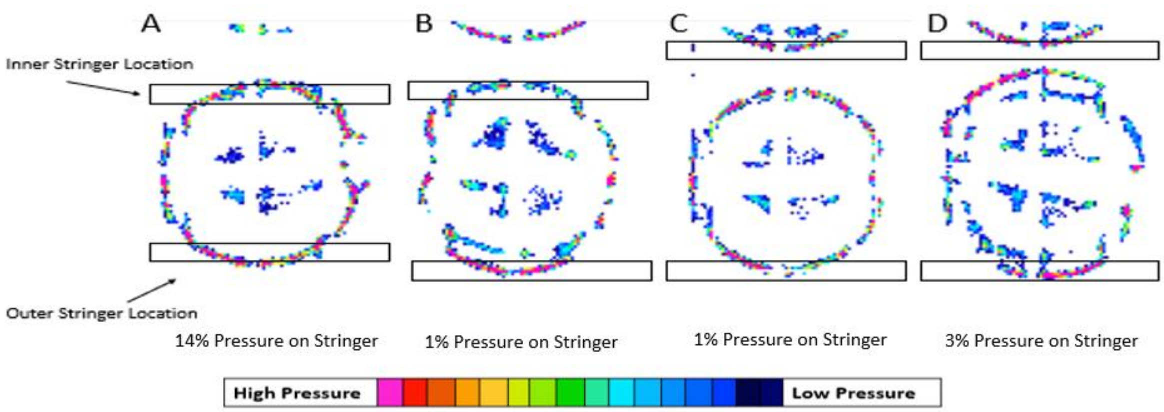

Fig. 17. Pressure distribution on stringer pallets carrying plastic drums using a double stack support condition. A) D1 pallet design, B) D2 pallet design, C) D3 pallet design, D) D4 pallet design

CONCLUSIONS

1. Out of the three loading methods, for most investigated conditions, metal drums caused the least pallet deflection, followed by the plastic drums, and then the airbag.
2. The effect of the loading method on pallet deflection was statistically significant for every single investigated support condition for all pallet designs. The greatest effect was found for the double stack support condition using metal drums; the deflection decreased 85% for the stringer pallets.
3. Metal drums distribute their pressure onto the pallet through their rigid chimes, which many times were mainly supported by the stringers, thus reducing the deflection of the pallet. Meanwhile, the plastic drums, because of their more flexible bottom design, distributed the pressure to the pallet deck boards resulting in greater pallet deflection.

4. More pressure was concentrated on the supports for metal drums than plastic drums, which indicates greater load bridging for the metal drums that could be responsible for the significantly lower pallet deflection observed.
5. When the percent of the pressure on the stringer was compared between the different pallet designs and the two drum materials, it was found that the pallet design (4-stringer vs. 3-stringer) and drum material (metal *vs.* plastic) both impacted the intensity of the pressure concentrations.
6. For some support conditions, the pallets loaded with plastic drums deflected more than the pallets loaded with an airbag. This finding is interesting because it is generally believed that airbag loading represents the worst-case scenario for many pallets. A possible explanation for the phenomenon could that the bending of the bottom of the plastic drums created a more concentrated force close to the middle of the deck boards, which could have increased their bending. The difference in the most extreme circumstances was 33%.
7. Pallets supporting metal drums deflected as much as 85% less than pallets loaded with the flexible airbag. The reduced deflection is attributed to the increased load bridging caused by the aspect ratio and stiffness of the metal drums. It indicates the potential for cost-saving opportunities when the load capacity of the pallet is limited by the pallet's deflection.
8. The effect of the loading method seemed to be dependent on the pallet's stiffness where the effect was greater for the lower stiffness pallet designs. This was mainly observed for the racking conditions.

These results indicate cost-saving opportunities, especially for pallets supporting metal drums in scenarios where the load capacity of the pallet is limited by pallet deflection when racked or stacked. However, it was also revealed that there is a significant difference in pallet behavior depending on the type of drum; therefore, the exact drum material and design need to be considered during pallet design.

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