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Effect of Pallet Deckboard Stiffness on Corrugated Box Compression Strength

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The packaging industry has long considered pallets to be rigid structures. However, in a unit load, the weight of the product produces compressive forces that are distributed across the pallet causing the top deckboards to deflect. Corrugated paperboard boxes are highly susceptible to changing support conditions; therefore, the deckboard deflection directly impacts the vertical compression strength of the box. Therefore, the objective of this study is to evaluate the effect of pallet deckboard stiffness on the vertical compression strength and deflection of corrugated paperboard boxes. Additional treatments included gaps between the deckboards and location of the box relative to the pallet stringers.

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KEY WORDS: stiffness; corrugated box; package; compression strength; pallet; unit load

INTRODUCTION

Corrugated boxes are ubiquitous in today's economy.[1] A large number of studies starting in the 1950s have developed empirical models to predict the compression strength of corrugated boxes.[2–10] These studies have identified a myriad of factors that determine the box compression strength including box size, shape, paper edge crush test value, flute size, corrugated paper bending stiffness and moisture content, among other factors.[3,5,11] Studies conducted by Ranger [4] and McKee *et al.* [5] adapted sandwich plate theory to corrugated paper using previous work on metal and wood, isotropic simply supported sandwich metal plates and non-isotropic plywood plates.[12–15]

In 1963, McKee *et al.* adapted non-isotropic plate theory to corrugated boxes in order to develop a box compression formula; however, non-uniform boundary conditions produced by creases, box flaps and paper variation have limited the reliability of the model.[5] Furthermore, McKee's model was relatively complex, and a simplified solution was produced for industry use. The simplification was accomplished by generalizing less significant theoretical variables and those that required specialty equipment for measurement.[5]

A unit load consists of corrugated boxes, or other products, that are secured on a pallet using stretch wrap or some other form of load containment. The unit load has become the primary mode of storage and shipment for packaged goods with 80% of domestic product moved in unit load form.[16] The large volume of unit loads requires an even greater supply of pallets. Current estimates place the pallet supply near two billion, making pallets nearly as ubiquitous as the corrugated box.[17]

The pallet provides support for the base layer of corrugated boxes within a unit load. The bottom layer of corrugated boxes is subjected to the highest compressive stress and is the most susceptible to failures generated by vertical compression.[18] Therefore, an improved understanding of the critical interface between box and pallet will improve the estimates of box compression strength.

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In 1957, McKee and Gander [19] found that a disproportionate amount of box compression strength was generated at the corners of the box. Kutt and Mithel [20] found that the amount of support provided to the box perimeter is directly related to compression strength of a box. Using a distinctly different method from McKee, the Kutt and Mithel study confirmed box corners to be stronger than box sidewalls. These findings raised concern about the uneven support provided by a wooden pallet.

A typical stringer pallet consists of bottom deckboards, stringers and top deckboards. The deckboards are the only components that directly interact with the bottom layer of corrugated boxes. Pallet deckboards are spaced along the stringer (or stringer board in a block pallet) leaving an unsupported gap. To simulate a unit load, Kellicut [21] tested the compression strength of a single layer of boxes on a pallet. When the results were compared with the same layer of boxes on a flat platen, the study found that boxes (empty or filled) lose approximately 12–13% of their compression strength.[22] Pictures from the study indicate that the boxes were subjected to a combination of unsupported sidewalls and corners. A box with unsupported corners is said to have 'overhang'. Overhang significantly reduces box and unit load compression strength, and packaging engineers actively design pallet patterns to eliminate this situation. By comparison, pallet gaps under the box sidewalls are unavoidable but less detrimental.

Several studies have endeavoured to quantify the effect of deckboard gaps on box compression strength. To simulate the effect, these studies used two rigid wood boards that could be moved to different gap distances. Typically, the box corners are fully supported, and the box is oriented so that the width panels will span the gap between deckboards. Ievans [22] found that a 76 mm gap had no significant effect on box compression strength while 127 and 178 mm gap reduced strength by 8 and 15%, respectively. Monaghan and Marcondes found that increasing the gap decreased box compression strength exponentially.[23] DiSalvo's experiment combined overhang treatments with gaps and found that the resulting drop in compression strength from the two treatments was not additive, with results 11% less severe than predicted if they were additive.[24] Each of these tests suggests that the strength reduction found in Kellicut's study should be far less or an additional variable has not been accounted for.[21]

To date, all studies of pallet gaps have utilized rigid boards to simulate the flexible deckboards of a pallet even though a myriad of studies have demonstrated that pallet deckboards deflect under load; the extent to which they deflect is dependent on product stiffness, stacking patterns and the quality of pallet components.[25–30] Deflection of the pallet deckboards adds a significant level of complexity to the distribution of forces within the unit load. Fagan first noted a phenomenon where a pallet deckboard deflected more than the product that it was supporting.[25] This discrepancy was labelled 'load bridging'. Load bridging can occur when layers of palletized product have a greater stiffness than the pallet.[25,27] Yoo found that load bridging produced greater stress concentrations at the box pallet interface, and this uneven distribution of force is not well understood.[28–30] In effect, the load bridging is a reduction in support to the box sidewalls. It is possible that the discrepancy between Kellicut's 1963 study and the findings of Ievans 1975 may have resulted from load bridging adversely affecting the box support conditions and thus reducing compression strength; however, the effect of flexible deckboards on box compression strength is unknown, and any additional interactions have yet to be quantified.[21,22]

OBJECTIVES

The objective of this study is to evaluate the effect of pallet deckboard stiffness on the vertical compression strength and stiffness of a corrugated paperboard box. Additional treatments included gaps between the deckboards and location of the box relative to the pallet stringers.

MATERIALS

Corrugated paperboard box

Production grade samples of 254 × 152 × 152 mm regular slotted containers were used in this study. The boxes were made of B-flute 5.6 kN/mm (32 lb/in) edge crush test corrugated paperboard. The

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boxes were manufactured at Corrugated Container Corporation, Roanoke, VA with industry standard manufacture joints and delivered knocked down, banded and palletized. Corrugated boxes were glued with hot melt adhesive. Two parallel beads of adhesive were applied to the top of the minor flaps. The major flaps were then folded inward, and the box was held in a jig to ensure squareness until the glue had cooled.

508 mm simulated pallet deckboard segments

In this study, 508 mm deckboard segments were built from materials capable of withstanding repeated testing without fatigue and thus maintain a constant stiffness. Three different pallet deckboard stiffness treatments were selected including one rigid and two flexible treatments. The two flexible deckboard treatments were specified so that their stiffness was comparable with high and low range of recycled wooden pallet top deckboards. The segments were constructed as follows:

Rigid deckboards (R) were produced using kiln-dried Southern Pine boards free of knots or other defects. The boards were cut to 508 × 152 × 38 mm specimens with perfect square edges (Figure 1).

Flexible deckboard segments consisted of deckboards made from poly(methyl methacrylate) (PMMA) commonly known as Plexiglas® (Figure 1). Decks were cut to 508 × 89 mm, with a thickness of 22 and 13 mm. The 22 mm were designated as the 'high' stiffness treatment ($EI = 155\,Nm^2$), while the 13 mm were designated as the 'low' stiffness treatment ($EI = 22.5\,Nm^2$) These high and low stiffness boards were specified based on a preliminary survey of used wooden pallets. The high and low stiffness is similar to the upper and lower range of these pallets.

The PMMA deckboards were predrilled and counter sunk to prevent cracking during assembly. Stringers were cut to 89 × 38 × 127 mm from Southern yellow pine. In order to produce a fixed joint between the PMMA and the wood stringer, a small amount of JB Weld® was applied to the deckboard and stringer contact before being screwed together with two 38 mm wood screws. Two assembled deckboard segments were then mounted to a 508 × 305 mm section of oriented strand board (OSB) using three 38 mm wood screws. The OSB acts as a bottom deckboard to prevent stringer movement while facilitating the accurate relocation of the pallet sections when simulating different gaps between the deckboards (Figure 2).

1016 mm simulated pallet deckboard segments

Additional full-length simulated pallet segments were produced using 1016 mm long and 89 mm wide PMMA deckboards and three pine stringers in order to simulate the full width of a typical stringer pallet. PMMA deckboards of two different thicknesses were used for this study including low 13 mm thick and medium 19 mm thick. The 19 mm thick PMMA was chosen because of lack of available 22 mm thick material in 1016 mm lengths. The stringers were mounted flush to each end of the deckboard, and one mounted directly in the centre and affixed to the deckboard in the same method as the 508 mm sections (Figure 3).

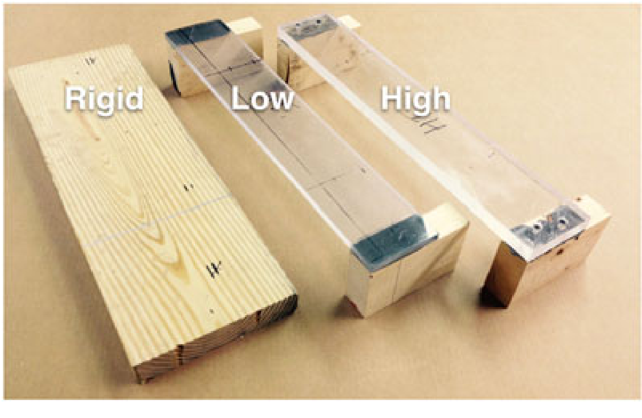

Figure 1. Representative 508 mm long deckboard segments for 'Rigid', 'High' and 'Low' treatments.

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Figure 2. High stiffness deckboard segments mounted to oriented strand board base with no span (0 mm) between deckboards.

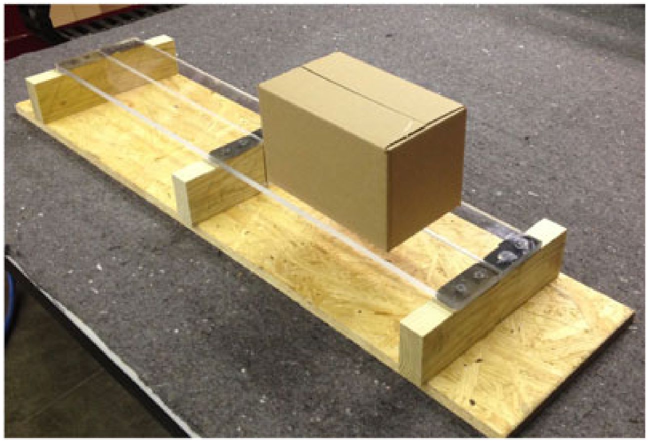

Figure 3. A photograph of full-length medium stiffness deckboards mounted to oriented strand board base with no span (0 mm) between deckboards. Box positioned at location 1 (centred between the stringers).

METHODS

Testing on 508 mm deckboard segments

The 508 mm long deckboard treatments and OSB base were placed directly on top of a rigid support platform (Figure 4a and b). Two holes were cut in the OSB platform to position two linear variable differential transformers (LVDTs – Schaevitz Model 200HR-DC, working distance ± 50 mm, accurate to 0.025 mm) in a location where pallet can be measured directly below the box corners (Figure 4). An additional LVDT (Schaevitz Model 100HR-DC working distance ± 25.4 mm) was mounted to the outside of the platform to measure any deflection in the test set-up, which was later removed from the total deflection. Deckboard deflection was measured at two diagonally opposite box corners. Deformation of the box was determined by subtracting the deflection measured by the LVDTs from the overall deflection measured by the MTS crosshead. The deformation at the corner was, in turn, used to calculate the stiffness at the box corners.

The corrugated box was centred on top of the pallet decks with the length parallel to pallet deckboard treatments. Load was applied with a rigid plate in the universal testing machine (MTS Systems Corporation model: 244.31) equipped with 4536 kg load cell (MTS Systems Corporation

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Figure 4. (a) Side 1 of the test set-up used to determine the effect of pallet deckboard stiffness on box compression strength. Dotted lines overlay LVDT locations. (b) Back side of test set-up. (c) Rigid deckboard set-up, no LVDTs.

MTS_10/GL). The crosshead speed was set to 13 mm/min per ASTM D642 and TAPPI 804 .[31,32] The compression testing was recorded with a video camera, and load and deflections were monitored using an automated data collection system. The boxes were loaded until buckling was observed on all four sides, or the force decreased over 20% from its peak compression strength.

For the rigid treatment, the deckboards were placed directly on the metal platen leaving no room to bend or deflect (Figure 4c). This also meant that there was no room for placing LVDTs. Only the cross-head was used to measure total box deformation.

To simulate a pallet, the deckboards were tested with 0 and 83 mm (3.25 in) gap between them. For the 0 mm set-up, the two deckboard segments were butted against each. In order to produce the 83 mm gap, one deckboard and stringer segment was repositioned 83 mm apart with the deckboards and stringers perfectly parallel so that the entire system was square. The 83 mm gap is typical for a wood pallet.

Testing on 1016 mm deckboard segments

The corrugated paperboard box was placed at three different locations on the pallet deckboard. The locations used were designated A, B and C (Figure 5). Location A was directly between two stingers and is equivalent to the testing conducted in the “Testing on 508 mm deckboard segments” section. For location B, the box is placed so that one panel is located directly over the centre stringer and the opposite side supported by the deckboard between the stringer segments. For location C, the box is centred over the centre stringer.

Compression testing was conducted a speed of 13 mm/min with a fixed platen using a Lansmont compression testing machine (Lansmont Corporation model: Squeezer 2268 kg load cell). The Lansmont allowed for the larger 1016 mm deckboards with the shortcoming of no auxiliary LVDT inputs.

Moisture content

Following the compression test, the moisture content of the corrugated paperboard was tested according to TAPPI 412.[33] Results from the compression testing were individually adjusted to 7.8% moisture content), equivalent to the moisture content of paperboard at 23°C and 50% relative humidity using the formula outlined by Kellicut and Landt (Equation 1).[2,34]

$$P = P_1 \frac{(10)^{3.01X_1}}{(10)^{3.01X_2}} \tag{1}$$

where X_1 and X_2 are moisture contents, P is the predicted compression strength of the box at X_2 moisture content and P_1 is the measured compression strength of the box at X_1 moisture content.

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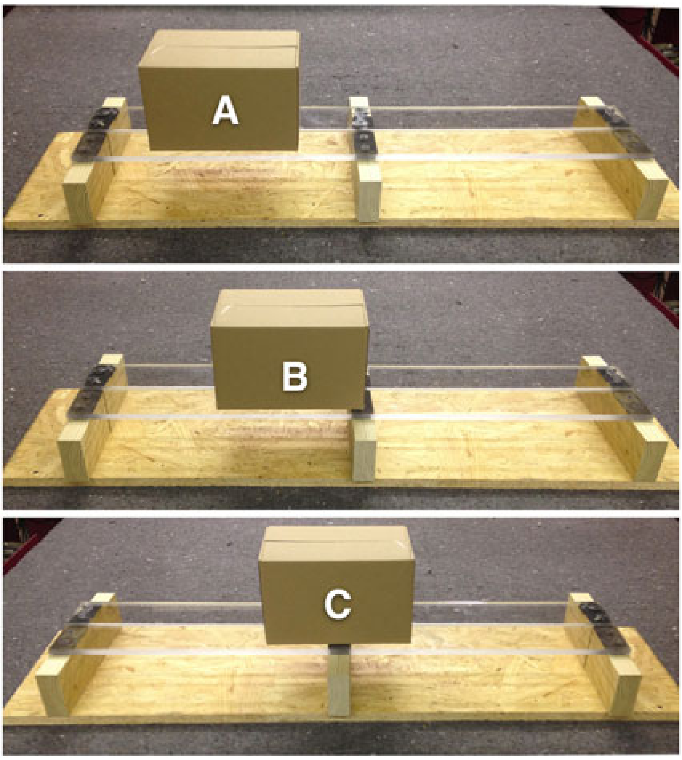

Figure 5. Picture of boxes positioned at each test location relative to the stringer.

DESIGN OF EXPERIMENT

To test the effect of deckboard stiffness on box strength and box stiffness, ten replicate boxes were compression tested on each 508 mm long deckboard: 'rigid', high and low. The test was conducted with deckboard gaps of 0 and 83 mm (Table 1). For all testing, the box was positioned between the stringer segments.

To test the effect of deckboard stiffness and box location on box compression strength, ten replicate samples were tested at each of the three box locations (Figure 5). The test was conducted using two different stiffness deckboards (medium and low) with no gap between deckboards (Table 1).

A one-way analysis of variance (ANOVA) was performed using SAS® JMP® software to analyse the difference between the sample means. Post hoc Tukey's honest significant difference testing was used to ensure that any significant differences in test results were evaluated conservatively ($\alpha = 0.05$).

Table 1. Experimental design: effect of pallet deckboard stiffness on box compression strength.

Deckboard size, mm (in)	Gap between deckboards, mm (in)	Box location	Deckboard stiffness levels			
			Rigid	High	Medium	Low
508 (20)	0	A	10	10		10
		B				
		C				
	83	A	10	10		10
		B				
		C				
1016 (40)	0	A		10	10	
		B		10	10	
		C		10	10	

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RESULTS AND DISCUSSION

Effect of pallet deckboard stiffness on box compression strength with and without gaps between deckboards

Table 2 shows that the stiffness of the pallet deckboards has a significant effect on the compression strength of a corrugated box when the pallet deckboards were butted directly against one another with no gaps between deckboards. A decrease in deckboard stiffness resulted in a decrease in box strength. The strength of boxes on high stiffness deckboards was reduced by 9.6%, while those on low stiffness deckboards experienced a 26.4% loss when compared with the boxes that were supported by the rigid deckboards. It is worth noting that the coefficient of variation increased as the pallet stiffness decreased.

When the deckboards had an 83 mm gap, there was no significant difference in box strength as deckboard stiffness changed (Table 2). All deckboard treatments at the 83 mm gap were 11.1–14.5% below the rigid-0 mm test. In this way, the addition of the 83 mm gap reduced the effect of deckboard stiffness. Figure 6 shows the compressive resistance provided by the box corners and shows clearly that the forces are not evenly distributed to the box sidewalls. In the picture, the length sidewall has buckled elastically while the width sidewalls and particularly the corners are buckling inelastically.

During testing, it was observed that the deckboards were experiencing torsion in addition to deflection. It is suspected that the concentration of forces at the box corners, which are much stronger than the sidewalls, is causing the PMMA deckboards to twist along their central axis. Figure 7 illustrates the ‘outward’ twisting of the deckboards with 0 mm gap and the ‘inward’ twisting of the deckboards at an 83 mm gap (B and γ). This twisting merited further exploration, as the rotation of the deckboards is likely to impart additional irregularities in the sidewall support conditions.[35]

Table 2. Summary table of box compression strength resulting from various deckboard stiffness treatments at 0 and 83 mm gaps between deckboards.

Deckboard stiffness	0 mm gap between deckboards				83 mm (3.25 in) gap between deckboards			
	Compression force, kg (lbs)	CoV (%)	Tukey’s HSD	Strength reduction (%)	Compression force, kg (lbs)	CoV (%)	Tukey’s HSD	Strength reduction (%)
Rigid	209 (461)	5.9	A	—	181 (399)	4.3	BC	—
High	189 (417)	6.5	B	-9.6	186 (410)	3.8	B	+2.6
Low	154 (339)	10.5	D	-26.4	179 (394)	7.2	CD	-1.3

Differences within the groups are determined using Tukey’s HSD at $\alpha = 0.05$. Results not connected by same letter were significantly different.

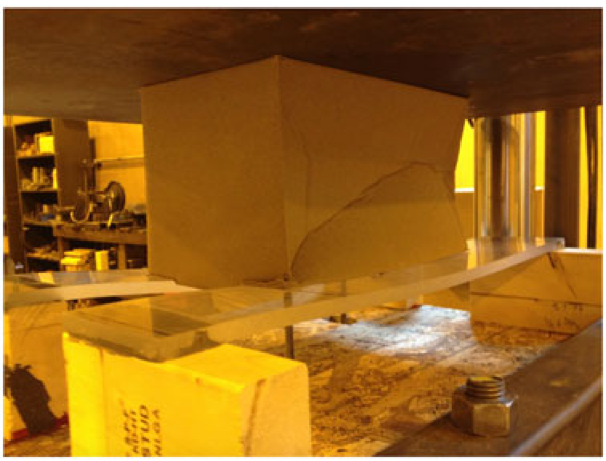

Figure 6. Front angle photograph of a box on low stiffness deckboard. Corner crush opposed to the buckling along the width sidewall.

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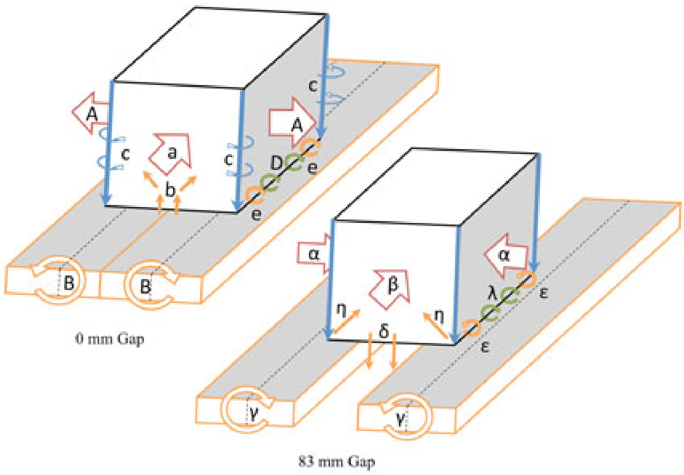

Figure 7. Illustrations of the hypothesized myriad forces acting on a box as deckboards with and without gap rotate.

Figure 7 shows some of the numerous forces acting on a box and how they change as the deckboards rotate. The sidewalls of a box are analogous to four plates with all four of their edges simply supported. During fully supported compression testing (i.e. rigid deckboards with 0 mm gap), the edge creases apply a moment to the sidewall that leads to outward buckling (D).[36] The longer of the two sidewalls is most susceptible to this moment and primarily fails outwards (A). Complexity is added by the fact that the vertical edges, the corners, are simply supported by the adjacent sidewall. Buckling in one sidewall produces a moment around the vertical corner (c), which applies a force into the adjacent sidewall, causing the adjacent sidewall to nearly always buckle in opposite directions.[36] Thus, outward failure of the length sidewall produces the moment around the vertical corners that forces the shorter sidewall to fail inwards (a). In this study, when the boxes were fully supported, the sidewalls failed in the described manor 9 out of 10 times.

In contrast to the full rigid support, the middle of the low stiffness deckboard was able to twist and bend. When the low stiffness deckboards were positioned with no gap between them, the corners of the box were pressing outside of the deckboard centreline causing the boards to twist outward (B). As the deckboard twists outward, an outward moment (e) is produced in the 254 mm long sidewall encouraging the wall to bend more outward and buckle at lighter loads. It was observed during testing that the 254 mm sidewall failed outward 10/10 times compared with a statistically similar 9/10 when the box was fully supported. In addition, as the deckboard rotated outward, the moment (c) around the corner increased and a force (b) was exerted on the centre of the 152 mm sidewall causing it to buckle at a lighter load (b). In total, the sum of these forces significantly reduce the strength of the box from what would be expected when there is no gap between deckboards.

When the low stiffness deckboards are spaced 83 mm apart, the box corners were positioned inside of the deckboard centreline causing it to twist inward (γ) and appearing as if to cradle the sidewall (η). This observation is supported by the fact that the 254 mm sidewalls failed outward (α) only 3/10 compared with 9/10 while fully supported on rigid decks (A) and 10/10 on low stiffness with 0 mm gaps. This change is caused by inward twisting deckboards (ε) resisting the natural outward moment produced by the flaps and creases (λ). Furthermore, the inward deflections of both panels (α and β) decreased the net moment around the corner (c) as observed when the panels fail in opposite direction (A and a). Finally, as the deckboards twisted inward, the stress being imparted to the relatively weak middle section of the 152 mm sidewall was reduced (δ as compared with b), thereby increasing the total box compression strength.

In a commercial application, the product inside the box may resist the inward buckling. It is recommended that further testing be conducted to determine if deckboard twisting is present in unit loads where multiple filled boxes will have their corners resting on the same deckboard and their sidewalls supported by products. Studies should consider testing low stiffness deckboards at more than one gap

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to determine if the trend continues as the box corners are moved along the deckboard perpendicular to the length.

In summation, stiffer pallet decks better support corrugated containers by limiting the loss in support conditions that develop when deckboards deflect and twist. This reduction in box compression strength is significant yet relatively small compared with other previously tested factors affecting box compression strength such as interlock stacking that reduces strength by 45%,[2] high relative humidity (90% relative humidity (RH)) that reduces strength by 57% and long-term storage (36 days) that can reduce stacking strength by 42%.[21] However, unlike humidity and storage time, the company has the option to purchase a variety of pallet styles and qualities. Reductions in a pallet strength and stiffness are a common result of cost and sustainability initiatives. Any changes made to pallet performance will necessitate additional safety factors or use of simulated deckboard testing to ensure that the corrugated box design is capable of performing as required.

Influence of box location on the relationship between deckboard stiffness and box compression strength

The results of compression testing at three pallet/box locations on two different deckboard stiffnesses (medium and low) are in Table 3. Box location on medium stiffness deckboards did not have a significant effect on the compression strength. For low stiffness deckboards, only location B was found to have a significant effect on box compression strength (−15.3%). Location B resulted in asymmetric loading when the two corners over the stringer were disproportionally loaded compared with the corners over the deckboard. By comparison, the boxes at locations A and C have similar forces at each of the four corners. In a typical pallet pattern, the majority of boxes will not experience even loading around their perimeter; therefore, location B could be analogous to the conditions most boxes will experience in a unit load.

Effect of deckboard deflection on box stiffness and deformation

In addition to the losses in compression strength, it was observed that the deckboard stiffness had a significant effect on box apparent stiffness (Table 4) and box deflection at failure (Table 5). As deckboard stiffness was reduced, the apparent stiffness of the box decreased significantly while the deformation at failure increased significantly. The apparent stiffness of the box decreased by 19.63 and 51.52% when supported by high stiffness and low stiffness deckboards with 0 mm gap between, respectively. When the same study was repeated over 83 mm gaps, the high and low stiffness deckboard treatments produced a decline in box stiffness of 19.9 and 61.6% compared with boxes on rigid treatment (Table 4).

Decreases in apparent stiffness are the result of the reduced effective bearing area, which concentrates the compressive force into a narrower range of the box sidewall. When the compressive forces are acting upon a smaller bearing area, the apparent stiffness of the box is reduced. This action is analogous to each nominal length of the sidewall acting as a spring with the sidewall acting as many

Table 3. Summary table of box compression strength at three locations on low and medium treatment pallet deckboards.

Location	A			B			C		
Deckboard	Compression strength, kg (lbs)	CoV (%)	Tukey's HSD	Compression strength, kg (lbs)	CoV (%)	Tukey's HSD	Compression strength, kg (lbs)	CoV (%)	Tukey's HSD
Medium	179 (395)	8.3	A	179. (395)	10.7	A	185 (408)	2.0	A
Low	174 (384)	10.3	A	152 (334)	7.7	B	180 (395)	3.4	A

Differences within the groups are determined using Tukey's HSD at $\alpha = 0.05$. Results not connected by same letter were significantly different.

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Table 4. Summary of box stiffness resulting from various deckboard stiffness treatments at 0 and 83 mm gaps between deckboards.

Deckboard stiffness	0 mm gap between deckboards				83 mm (3.25 in) gap between deckboards			
	Stiffness[a] kg/mm (lbs/in)	CoV (%)	Tukey's HSD	Stiffness reduction (%)	Stiffness[a] kg/mm (lbs/in)	CoV (%)	Tukey's HSD	Stiffness reduction (%)
Rigid	46 660 (4050)	17.1	A	—	38 090 (3306)	13.8	B	—
High	37 500 (3255)	11.1	BC	-19.6	30 513 (2648)	7.3	C	-19.9
Low	22 619 (1963)	35.5	D	-51.5	14 610 (1269)	18.8	E	-61.6

Differences within the groups are determined using Tukey's HSD at $\alpha = 0.05$. Results not connected by same letter were significantly different.
[a]Box stiffness measured at corner.

Table 5. Box deformation at failure as a result of deckboard stiffness at 0 and 83 mm gap between deckboards.

Deckboard stiffness	0 mm gap between deckboards				83 mm (3.25 in) gap between deckboards			
	Deformation at failure[a] mm (in)	CoV (%)	Tukey's HSD	As % of total box height	Deformation at failure[a] mm (in)	CoV (%)	Tukey's HSD	As % of total box height
Rigid	5.8 (0.23)	6.7	A	3.9	5.3 (0.21)	5.7	A	3.5
High	6.4 (0.25)	14.5	A	4.1	6.1 (0.24)	12.6	A	4.0
Low	10.7 (0.42)	20.0	B	7.0	17.0 (0.67)	5.9	C	11.1

Preload of 23 kg according to ASTM D-642. Differences within the groups are determined using Tukey's HSD at $\alpha = 0.05$. Results not connected by same letter were significantly different.
[a]Box deformation measured at corner.

springs in parallel. By reducing the bearing area, the number of springs is reduced and the stiffness decreases accordingly.

A decrease in box apparent stiffness does not necessarily coincide with an increase in box deflection at failure. The box deflection at failure results for the three investigated pallet deckboard stiffness are presented in Table 5. Boxes on high stiffness deckboards, both with and without the 83 mm gap, did not experience a significant change in deformation at failure compared with those on rigid deckboards. However, the deformation at failure of boxes on low stiffness deckboards increased by 82.6 and 219% compared with the rigid deckboards when positioned over 0 and 83 mm gaps, respectively. The dramatic increase in box deformation at failure on low stiffness deckboards is suspect to be closely related to the changing support conditions along the middle of the box sidewall. The uneven distribution of load suggests that there will be an equally uneven deformation at the box corners and the box sidewalls. During testing, it was observed that the centre of the deckboard deflects more than the centre of the box (Figure 6). These observations confirm previous work by Fagan 1982,[23] Collie 1984 [24] and Yoo 2008 and 2011, who found that deckboards can deflect more than the package resting on top of the deckboard, which results in the centre of the packaging becoming unsupported.[25,26,28,29] Figure 6 shows that the corners of the box are crushing during testing, yet the width sidewall has not buckled or yielded fully. This differs substantially from the normal mode of failure where the sidewalls of the box buckle in a crescent shape before any crushing of the corner occurs. The increase in deflection at the corners of the box presents a problem for box designers because a box designed to have proper headspace protecting the product inside will be unable to perform as intended if it is supported by a low stiffness pallet deck. Additionally, the data indicates that a pallet deckboard stiffness threshold exists where increasing deckboard stiffness has a diminishing influence on the deflection at failure. While below this threshold, any decrease in deckboard stiffness produces significantly greater deflections at failure.

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CONCLUSIONS

The results indicate that deckboard stiffness and bending have a significant effect on box compression strength and box deformation.

1. The bending stiffness of the pallet deck has a statistically significant effect on the compression strength of a box, when there is no gap between the deckboards.
2. When compared with a standard box compression test, the change in pallet deck stiffness reduced the average box compression by 26.4%. However, when a gap between deckboards of 83 mm is introduced, the pallet deck stiffness did not affect box compression. Observations during testing indicate that the gap allowed the deckboards to rotate that altered the direction and magnitude of the forces on the box corners and sidewalls. This effect requires further study.
3. On a low stiffness pallet deckboard, the effect of box placement relative to the stringers reduced box compression strength by 15.3% when two of the four corners were over the stringer.

Box size and stacking patterns will change the location of the box relative to the deckboard centreline producing any number of complex interactions as the decks rotate. Box designers should consider deckboard stiffness when conducting laboratory testing. However, no standard method exists for adjusting safety factors or box design criteria.

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