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Predicting the Effect of Gaps Between Pallet Deckboards on the Compression Strength of Corrugated Boxes

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Cover Page Footnote

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RESEARCH ARTICLE

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ABSTRACT

The majority of corrugated boxes are transported and stored on pallets where the reduced support area due to deckboard gaps has an adverse effect on the strength of the corrugated boxes Therefore, an adjustment factor is used to adjust the box compression strength to account for the lack of support, but these factors were developed for a limited range of deckboard gaps, box sizes, and box orientations. In addition, there is no predictive model that can estimate the reduction in compression strength based on the size of the box and the size of the gap. The main objective of this study was to investigate and predict the loss in compression strength produced by top deckboards with a wide range of gaps between them using empirical data from two different corrugated box sizes.

Results indicated that corrugated box compression strength decreased as the gap between the pallet deckboards increased. Larger boxes (305mm wide) were far less susceptible to the effect of gaps than the smaller boxes. A decrease in strength was observed when the location of the gap was relocated within 10 mm of the box corner. Gaps were found to produce the same reduction in compression strength when subdivided into two smaller gaps. Finally, a modification of the McKee equation was put forth and the analysis found the equation to be capable of predicting the loss in compression strength produced by gaps. The predictive accuracy was similar to the original McKee equation, and thus equally limited by the inherently large variation in corrugated boxes.

KEY WORDS: *pallet, corrugated, box, compression, package, unit load*

1.0 INTRODUCTION

A unit load consists of packaged products, a containment method such as stretch wrap, and a pallet. Eighty percent of all domestic products are shipped in unit load form [1]. When products are unitized they are easier to handle, store, and transport [2]. Within a unit load, the box primarily experiences vertical compressive loads that can cause buckling and damage to the box and its contents [3]. Therefore, the ability to predict the compression strength of any box design reduces development time and ensures damage free products [4]. To date, studies have focused on producing equations capable of predicting the compression strength of a box resting on a flat surface. Notable studies of box compression strength include Kellicutt and Landt 1951 [5], Maltenfort, 1956 [6], Ranger 1960 [7], McKee 1963 [4], Kawanishi 1988 [8], Batelka and Smith 1993 [9], Biancolini and Brutti 2003 [10], Urbanik and Saliklis 2003 [11]. Corrugated paper varies significantly; thus, accurately predicting box strength is difficult. Each study has made a significant contribution; however, the simplified McKee equation is still the industry standard. The "simplified" McKee equation (1) has two distinct advantages: 1) ease of mathematical interpretation, and 2) the use of readily available box characteristics that do not require laboratory testing.

Since the late 1960's, efforts have been made to better identify the factors impacting the compression strength when boxes are moved in commercial supply chains. However, "little is known about the behavior of a corrugated box containing products stacked on a pallet" [12]. Kutt and Mithel (1968) found that the compression strength of a box is directly related to the amount of support provided to the box perimeter [13]. To simulate a unit load, Kellicut (1963) tested a single layer of boxes on a pallet and compared the results to boxes on a flat platen [14]. The study indicated that boxes (empty or filled) lose approximately 12-13% of their compression strength when they are on a pallet. Singh et al. studied four different box sizes stacked on block and stringer pallets. The study indicated that boxes stacked on CHEP® block style pallets have greater compression strength than boxes stacked on a grocery manufacturers association (GMA) style stringer pallet [15]. Singh proposed that the difference is due to the CHEP® pallet having a greater top surface area than GMA stinger pallet. The study also found that some loss in box compression strength could be mitigated when a tie-sheet (a layer of thick paper or corrugated) is placed between the boxes and the pallet [15],[16].

Ievans 1975, Monaghan and Marcondes 1992, and DiSalvo 1999 have all studied the effect of gaps between deckboards on box compression strength. Ievans found that 127 mm and 178 mm gaps reduced compression strength by 8% and 15%, respectively [17]. The study utilized a relatively large 610 mm x 394 mm x 305 mm C-flute box. Ievans also found that gaps of less than 76 mm had no apparent effect on compression strength of the box. Monaghan and

(EQUATION 1)

$$P = 5.87 P_m \times \sqrt{h \times Z}$$

Where:

$P =$ box compression strength (kg)

$P_m =$ edgewise compression strength of corrugated board (kg/mm)

$h =$ combined board caliper (mm)

$Z =$ box perimeter (mm)

Marcondes 1992 produced the first equation for predicting the effect of gaps between deckboards and found that box compression strength declined exponentially as the gap was increased [18]. The equation produced by Monaghan and Marcondes is limited to 400 mm x 270 mm x 170 mm C- flute boxes. DiSalvo's (1999) study evaluated a combination of overhang (two unsupported box corners), gaps between deckboards and interlock stacking patterns to determine if the loss in compression strength was additive when factors occurred simultaneously [19]. The study included three different pallet gaps, 5%, 15% and 25% of the box area, which correlate to 8 mm, 23 mm and 38 mm. The study indicated that combining overhang and gaps did not produce an additive drop in compression strength. Instead, the total compression strength loss was 11% less than predicted.

To date, box compression testing has been conducted on a narrow range of deckboard gaps and always with the box oriented so that the width panel is centered over the gap. Additionally, McKee demonstrated that the corners of a box support a far greater load than the center of the sidewall [20]. In previous studies the boxes were centered over the deckboard gaps. Rarely does this occur in commercial unit loads so gaining an understanding strength reductions resulting from box location over gaps will benefit unit load designers.

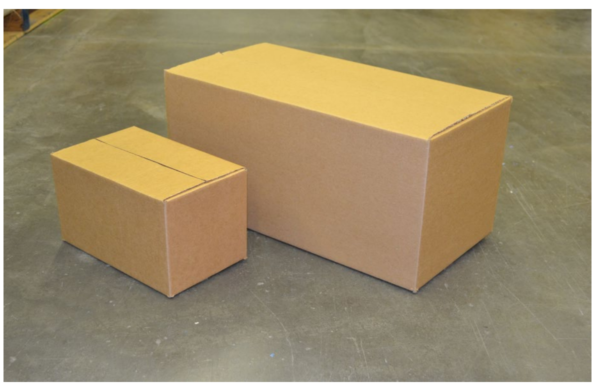

Figure 1: Side-by-side comparison of assembled RSC sample boxes:
254 mm x 152 mm x 152 mm (front left)
508 mm x 305 mm x 305 mm (back right)

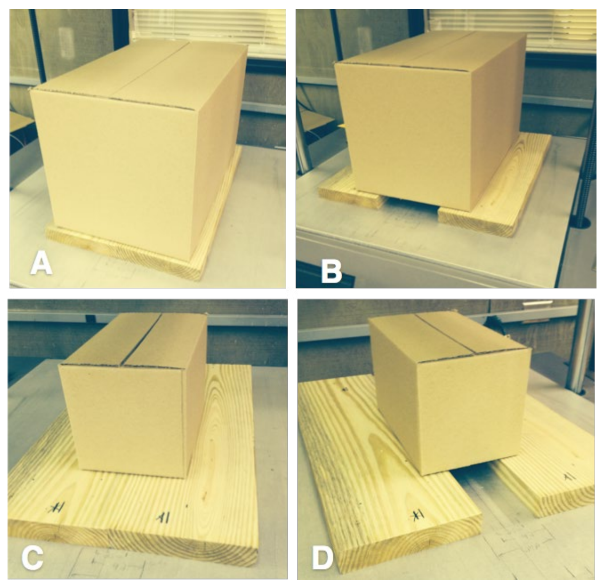

Figure 2: Experimental setup with boxes centered on deckboards inside the Lansmont compression tester.
A) "Large" box on 0 mm gap.
B) "Large" box on 165 mm gap under width panel.
C) "Small" box on 0 mm gap.
D) "Small" box on 83 mm gap under width panel.

2.0 OBJECTIVE

The general objective of the study was to investigate and predict the compression strength of corrugated boxes supported by rigid pallet top deckboards with gaps. The specific objectives of the study were to:

- Determine the effect of gaps between pallet deckboards on the compression strength of 254 mm x 152 mm x 152 mm and 508 mm x 305 mm x 305 mm corrugated boxes.
- Determine the effect of the location and number of gaps between pallet deckboards on the compression strength of 254 mm x 152 mm x 152 mm corrugated boxes.
- Modify the McKee equation to predict the compression strength of corrugated boxes supported by rigid pallet deckboards with gaps

3.0 MATERIALS

3.1 Corrugated Paper Board Box

Regular Slotted Container (RSC) style boxes were made of 32 ECT (Edge Crush Test) B-flute corrugated paperboard in two sizes: 254 mm x 152 mm x 152 mm and 508 mm x 305 mm x 305 mm were used in this study (Figure 1). Corrugated Container Corporation of Roanoke, Virginia manufactured the boxes.

3.2 Pallet Deckboards

Two 508 mm x 152 mm x 38 mm boards were prepared from Southern Pine with 90-degree angles at each edge. The wooden boards were continuously supported and were placed at varying distances apart to simulate different gap sizes. Actual pallet deckboards deflect under load due to their Modulus of Elasticity and the unsupported span between the stringers/blocks; therefore, the fully supported boards used here only serve to simulate the effect of spacing between deckboard.

(EQUATION 2)

$$\text{Moisture Content \%} = \frac{(W_1 - W_2)}{W_2}(100)$$

Where W_1 = Sample weight before drying

W_2 = Sample weight after drying

(EQUATION 3)

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

Where

P = compressive strength

P_1 = known compression strength of box

X_1 = moisture content for box having P_1 compression strength

X_2 = moisture content of box for which the compressive strength is to be determined

4.0 METHODS

4.1 Compression Testing

The boxes were placed on the wooden boards so that the box sidewall being tested was centered over the gap (Figure 2). A compression table (Lansmont Corporation Model: Squeezer) equipped with a 2,267 Kg load cell was used to apply force to the boxes with a fixed platen, at a speed of 12.5 mm/min. according to TAPPI T-804 [21].

4.2 Moisture Content Determination

The moisture content of the box was determined according to the TAPPI 412 testing standard [22]. Using Equation 3 the compression testing results were adjusted to standard laboratory testing conditions of 23℃ and 50% relative humidity. [5,14]

4.3 Edge Crush Test

50 mm x 50 mm samples were taken from 10 non-tested boxes and tested for Edge Crush Test values using the TAPPI T811 waxed edge method [23].

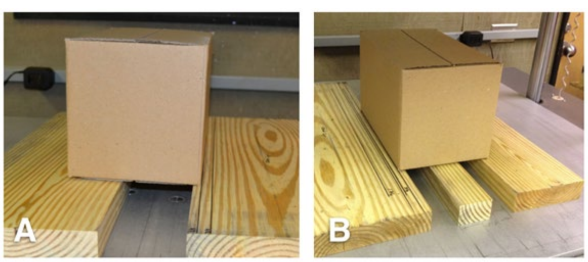

Figure 3: A) The 254 mm x 152 mm x 152 mm box supported by deckboards with 83 mm and positioned off-center by 13 mm. B) Test setup for double-gaps between deckboards using three simulated deckboard segments with two 42.5 mm gaps, which total 83 mm.

5.0 DESIGN OF EXPERIMENT

5.1 Effect of Gaps on Box Compression Strength

The 254 mm x 152 mm x 152 mm (LxWxD) "Small" box was tested over deckboards gap of 0 mm, 15 mm, 23 mm, 38 mm [1.5 in.], 64 mm, 83 mm [3.25 in.] under the width sidewall and 0 mm, 38 mm, 64 mm, and 140 mm under the length sidewall. The 508 mm x 305 mm x 305 mm "Large" box was tested over gaps double in size to keep the percent of unsupported area under the sides the same as what was used for the "Small" boxes. This represents the relatively high likelihood that the "Large" box would span multiple deckboards on commercial pallets. Ten replicate tests were performed over each gap. Gaps were limited to 55% of box sidewall length for practical reasons.

5.2 Effect of Location and Number of Gaps on Box Compression Strength

To determine the effect of location, the 254 mm x 152 mm x 152 mm box was shifted horizontally by 13 mm and 25 mm while the gap between deckboards remained 83 mm (Figure 3A).

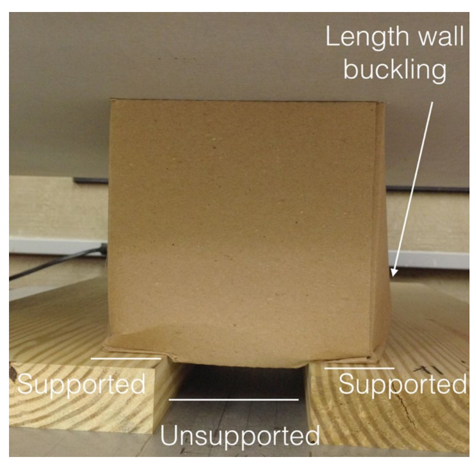

Figure 5: Picture of "Small" box failure showing failure due to bucking of the right sidewall.

Gap Offset from Center (mm)	**Support Left Side (mm)**	**Support Right Side (mm)**	**Center Support (mm)**	**Total Gap (mm)**
0	34.5	34.5	0	83
13	47.5	21.5	0	83
25	59.5	9.5	0	83
Double-Gaps	42.5	42.5	50	83

Table 1: Summary table of support provided by deckboards when box is positioned off-center from the gap and spanning multiple gaps.

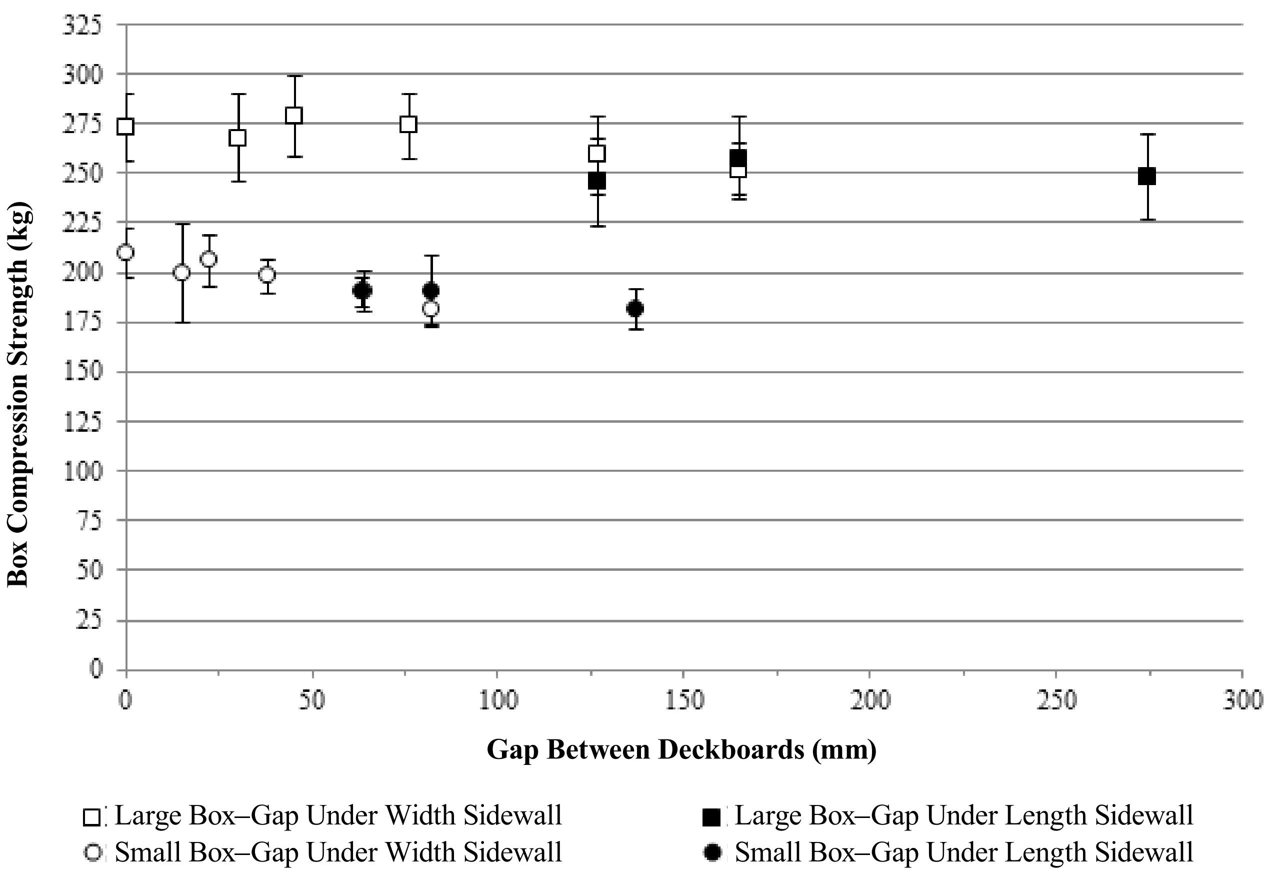

Figure 4: The effect of gaps on the compression strength of 508 mm x 305 mm x 305 mm "Large" box and 254 mm x 152 mm x 152 mm "Small" boxes.

To analyze the effect of the number of gaps, a third deckboard was cut to 508 mm x 50 mm x 38 mm. The 50 mm wide board was centered between a larger 133 mm gap (Figure 3B) so that the resulting 83 mm gap was split equally into two 42.5 mm gaps. A summation of all treatments has been provided in Table 1.

6.0 RESULTS AND DISCUSSION

6.1 Effect of Gaps between Deckboards on Box Compression Strength

Testing indicated that the gaps had a relatively small, but statistically significant effect, on all box and sidewall combinations (Figure 4). The "Small" box experienced significant reduction in strength at 64 mm (2.5 in.) and a maximum strength reduction of 13.4% at 83 mm gap (3.25 in.) along the width sidewall. The coefficient of variation within treatments ranged from 3.2% to 9.5%, which masks much of the effect at small gap sizes. The results are similar but less than the Monaghan and Marcondes' model, which predicts a 17.6% reduction at the 83 mm gap [18]. The results did not match DiSalvo who found a 10.4% reduction at 15 mm. This study indicated such a small gaps to have no effect [19]. The small sample size and lack of moisture hysteresis control in DiSalvo's study is the likely source of the difference.

The magnitude of the gap effect was less for the "Large" box than the "Small" box. Only the 166 mm width sidewall gap and all of the length sidewall gaps were significantly lower in compression strength. The strength reduction of the largest gap 9.2% was observed at 280 mm (11 in.) along the length sidewall of the "Large" box. The coefficient of variation was spread between 5.3% and 8.8% (Figure 4). The results are in line with that of Ievans who also used a similarly sized large box. At 178 mm (7.0 in.) the Ievans study found a 15% reduction in strength while this study found a 7.8% reduction albeit at a slightly smaller 165 mm (6.5 in.) gap [17].

When the same size gap was placed under the length or the width panel the reduction in box compressing strength was statistically similar. The largest gap used in this study was positioned under the length panel and the resulting strength reduction followed the same trend in compression strength reduction (Figure 4).

Box sidewalls are known to buckle when a critical stress is reached [24]. As the gap increases the bearing area decreases; therefore, the stress increase and less load is required to reach the critical buckling stress (Figure 5).

6.2 Effect of Location and Number of Gaps on Box Compression Strength

It was found that changing the location of the 83 mm gap affected the strength of the box. Box compression decreased as the gap was moved closer to the box corners. At 13 mm and 25 mm offset from center, the box compression was reduced by 2.3% and 5.4 %, respectively. However, only the 25 mm offset was found to be significant by the post hoc student's T test (Table 2). Additionally, testing showed that the 83 mm gap could be subdivided into a double-gap without significantly affecting the box compression strength.

6.3 Modified Perimeter McKee Model

Previous studies, and the findings above, suggest that the McKee equation (1) can be modified to predict box compression strength even when a box is supported by deckboards with a gaps between them.

Previous studies have addressed the effect of gaps between deckboards as a two dimensional problem where a single sidewall is crossing a single gap [17], [18], [19]. A 83 mm gap between deckboards is said to remove 83 mm of support or ~54% from a 152 mm long sidewall. However, a box is a three-dimensional structure and any gap between deckboards will affect two opposite sidewalls (Figure 6). For example, a gap of 83 mm between deckboards will affect both front and back width panels for a total of 165 mm (~20.3%) reduction in support to the perimeter.

Kutt and Mithel 1968 established that the strength of a tube (box without flaps) is directly related to the support provided to the sidewall [13]. McKee (1963) identified three necessary inputs needed to predict the compression strength of a box: edge crush test (ECT) value, board caliper, and box perimeter (Equation 1) [4]. McKee discovered that the relationship between box perimeter and compression strength was not linear; as the size of the box increases there was a diminishing return in compression strength. The results presented above, and those of Monaghan and Marcondes (1992), confirm that the box compression strength and gaps size/perimeter support are not proportional [18].

Monaghan and Marcondes (1992) first proposed a modification to the McKee Equation (1) that would predict the effect of box "overhang" (two corners and one sidewall unsupported) by subtracting any length of unsupported sidewall from the box perimeter [18]. Monaghan ultimately deemed the method unsuccessful due to high variability. However, the team did not attempt to use this proposed modification to predict the effect of gaps between deckboards.

Based on the correlation between the perimeter and the strength of the box, a modification to the McKee equation was developed (Equation 4). The gap between deckboards (G) is doubled to account for the loss of support at two opposite panels, which is then subtracted from the box perimeter (Z). Note that this equation is only applicable to RSC boxes of perimeters less that 135 in. as required by the original McKee equation.

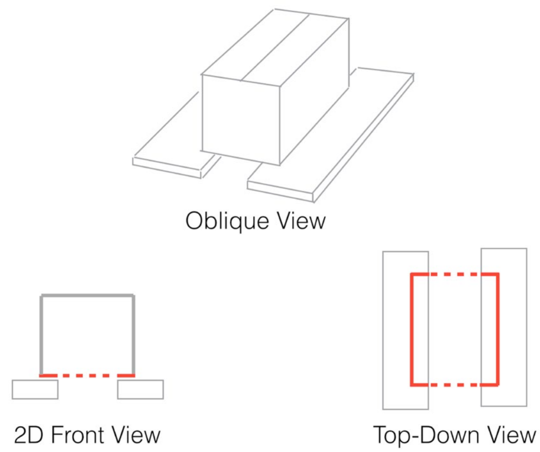

Figure 6: Representation of 254 mm x 152 mm x 152 mm box showing oblique view (top). Front view with dotted line representing the loss in sidewall support caused by the gap between deckboards (left), and top-down view with dotted line representing the loss in perimeter support caused by the gap.

Gap Offset from Center (mm)	**Compression Strength (kg)**	**Student's T Test**
0	189 (4.33)	
13	185 (2.91)	P = 0.1877
25	179 (2.72)	P = 0.0030*
Double Gaps	187 (4.88)	P = 0.5702

Table 2: Summary table of boxes compression test results at different locations and number of gaps. Note: values in parentheses are Coefficient of Variation values.
** significantly different from control by Student's-T Test at α=0.05.*

To analyze the usefulness of Equation (4), the box compression data was compared to the equations predicted compression strength. The edgewise compression strength (ECT) listed on the box manufacturers certificate (BMC) is a conservative estimate of ECT and would dramatically affect the predictive accuracy of equation (4). Therefore, samples removed from new, untested boxes, were tested according to the TAPPI T-811 method and the ECT of the corrugated board was found to be 0.67 kg/mm (equivalent to 37.5 lb/in). Equation (4) under estimated the actual compression strength by an average of 13.2 kg with an average error of 8.2% (Black line Figure 7) when box strength was calculated using the tested ECT value. While under estimating box strength is far safer than over estimation it is important to emphasize that the original McKee equation and any modification to it will only be as accurate as the input data. The majority of under estimates were in regards to the smaller box size. The McKee equation does not account for height and thus taller boxes are weaker than a shorter box of the same perimeter.

The proposed McKee Modification can also be used to adjust an empirical box compression test (BCT) control value as a function of the size of the pallet gaps (5). In this way a known BCT for a particular box can be adjust to account for pallet gaps. Equation 5 under predicted box strength by 6.8kg with and average error of 5.8% and 95% of the error with 6.5% (Red line Figure 7). As an additional note, the original McKee equation had an average error of 8.5% for B-Flute boxes. In this study, the compression strength was adjusted for moisture content using the Kellicut equation (3). Had this moisture content adjustment not taken place the average error using Equation 5 (Red Line) would have been 8.6%. Therefore, adjusting for moisture content represents a 32% reduction in error.

(EQUATION 4)

$$P = 5.87 P_m \times \sqrt{h \times (Z \times 2G)}$$

Where:

$P =$ box compression strength (kg)

$P_m =$ edgewise compression strength of corrugated board (kg/mm)

$h =$ combined board caliper (mm)

$Z =$ box perimeter (mm)

$G =$ gap between deckboards (mm)

(EQUATION 5)

$$GBCT = BCT \times \sqrt{\frac{Z - 2G}{Z}}$$

where:

$GBCT =$ gapped box compression strength (kg)

$BCT =$ box compression strength (kg)

$Z =$ box perimeter (mm)

$G =$ gap between deckboards (mm)

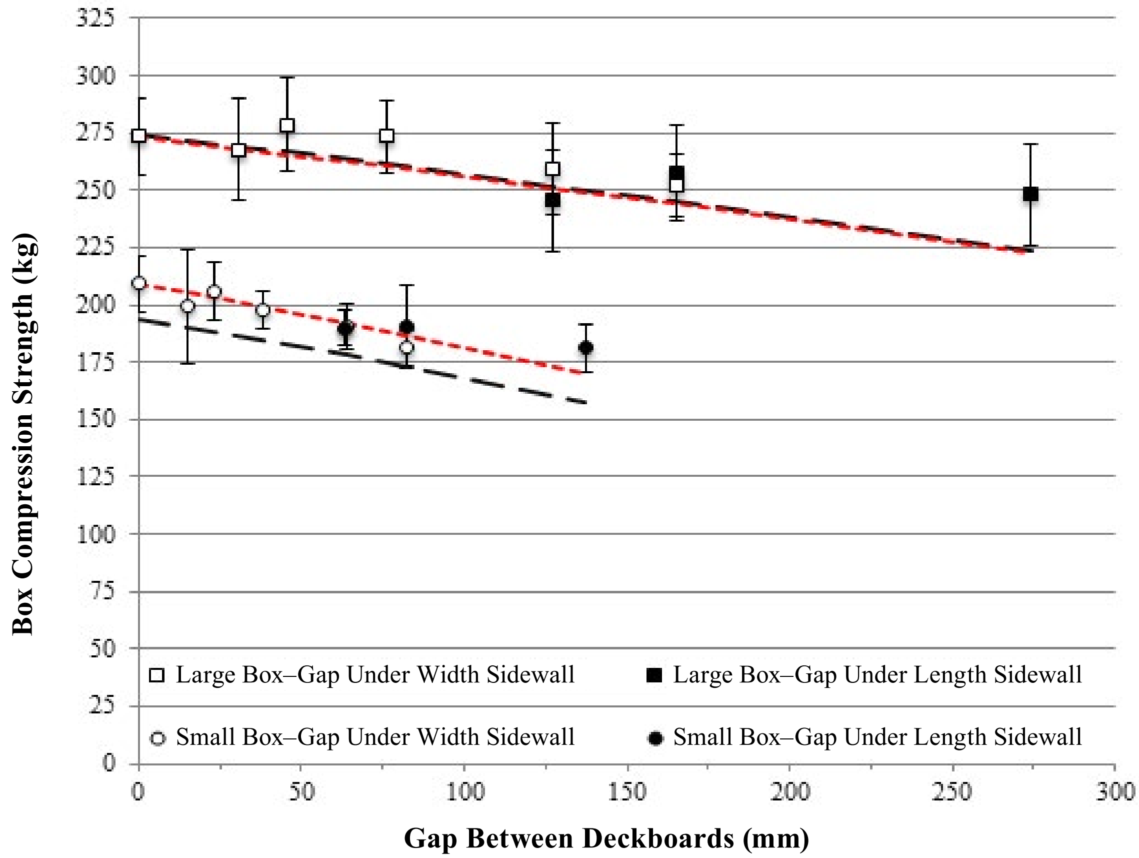

Figure 7: The effect of gaps on the compression strength of 508 mm x 305 mm x 305 mm "Large" boxes and 254 mm x 152 mm x 152 mm "Small" boxes. Grey line represents predicted values using the 37.5 ECT while the red dotted line represents predicted values normalized to 0 mm gap.

In summation, the original and modified McKee equation is highly dependent on the quality of data being input into the equation. However, the Modified McKee looks to be a promising method for addressing a range of deckboard gaps but is not a global solution. Gaps were limited to 55% of box sidewall length for practical reasons and only two box sizes were tested. Furthermore, the equation is also limited by the original McKee constraints including RSC application only and limited box sizes.

The strength of the Modified McKee is its industry friendly application. However, three distinct problems remain. First, there is no agreed upon method for integrating a predictive equation with the current safety factor system. Second, this research was conducted on single empty boxes and does not reflect commercial use where filled boxes are shipped and stored in a unit load. Third, the inherently high variation in corrugated boxes masks much of the gap effect indicating that gaps may be less concerning than paper consistency or moisture content.

7.0 CONCLUSION

- Similar reductions in strength were found when boxes were oriented with the width and length sidewall over identical gap sizes.
- Larger 508 mm x 305 mm x 305 mm boxes are less susceptible to the effect of gaps (5% reduction at 127 mm gap which is 7.8% of the total perimeter) compared to the smaller 254 mm x 152 mm x 152 mm boxes (5% reduction at 38 mm which is 4.7% of the total perimeter).
- The effect of gap number with two 42.5 mm each (total 83 mm or 3.25 in.) is statistically the same as a single 83 mm gap on box compression.
- Changing the location of the gap significantly affects the strength of the box.
- A modification to the McKee equation was developed to account for gaps between deckboards. The proposed equation is limited to RSC boxes meeting the original McKee requirements and spanning gaps no more than 55% of the sidewall being intersected. The proposed equation has a similar error to the original equation with both being limited by the inherent variation in corrugated boxes.

8.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Future studies are encouraged to validate the proposed model under a wider variety of conditions and greater sample rate. The accuracy of the Modified McKee Equation can also be improved by revisiting McKee's simplification process (McKee 1963), by factoring in box height according to Batelka and Smith's equation (1993), and by testing more length-width ratios. The effect of gaps between deckboards on box compressions strength research should be expanded to include filled boxes, additional flute sizes, and other box styles. Future studies should also consider testing the effect of gaps across full unit loads of product to determine if these findings can scale up to full unit loads.

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