Effect of Pallet Deckboard Stiffness and Unit Load Factors on Corrugated Box Compression Strength

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ABSTRACT

Corrugated paper boxes are the predominant packaging and shipping material and account for the majority of packaging refuse by weight. Wooden pallets are equally predominant in shipping, transportation and warehousing logistics. The interaction between these two components is complex and unexplored leaving industry to compensate with outdated component specific safety factors. Providing a focused exploration of the box and pallet interaction will open the door for holistic design practices that will reduce cost, weight, damage, and safety incidents. This study was separated into four chapters exploring different aspects of the corrugated box to pallet interaction.

The first chapter evaluates the support surface provided by a pallet consists of deckboards spaced perpendicular to the length of the pallet. The resulting gaps between deckboards reduce the support to the box. Gaps were limited to 55% of box sidewall length for practical reasons. The effect of gaps was significant and produced a nonlinear reduction in box strength. Small boxes were more susceptible to gaps than larger boxes. Moving the gap closer to the corner increased its effect while increasing the number of gaps did not increase the effect. A modification to the McKee equation was produced that was capable of predicting the loss in strength due to gaps. The equation is novel in that is modifies a widely used equation and is the first such equation capable of handling multiple box sizes. This study also has practical implications for packaging designers who must contend with pallet gap.

Chapter 2 explores the relationship between deckboard deflection and box compression strength. Testing found that reducing the stiffness of the deckboard decreases the compression strength of the box by 26.4%. The location of the box relative to the stringer also had varying effects on the box strength. A combination of deckboard stiffness and gaps produced mixed with results with gaps reducing the effect of stiffness. It was observed that lower stiffness deckboards not only deflect but also twist during compression. The torsion is suspected to have a significant influence on compression but further exploration is needed.

The third chapter tests the effect of box flap length on box compression strength under various support conditions. Variables included four flap lengths, gaps between deckboards, low stiffness deckboards, column stacking and misaligned stacking. The results show that the box flaps can be reduced by 25% with no significant effect of box strength under any support condition tested. Furthermore, the box flap can be reduced by 50% with less than 10% loss in compression strength under all scenarios. These results have significant sustainability implication as 25% and 50% reduction in box flap reduce

material usage by approximately 12% and 24%, respectively.

In the fourth and final chapter, the theory of beam-on-elastic foundation is applied to deckboard bending and corrugated boxes. In this model the corrugated box acts and the foundation and the deckboard is the beam. Rotational stiffness, load bridging, and foundation stiffness changes required the development of novel testing solution and model development. The model was capable of predicting the distribution of force along the length sidewall but was not capable of predicting the ultimate strength of the box. The model developed in the study will be applicable in determining potential weakness in the unit load in addition to optimizing those that are over designed.

These four chapters represent a considerable contribution of applicable research to a field that relied on outdated safety factors over thirty years. These safety factors often lead to costly over design in an industry where corrugated box and pallets volumes make event the smallest improvements highly beneficial. Furthermore, this research has opened the door for significant additional research that will undoubtedly provided even greater economic and sustainability benefits.

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LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1 Corrugated Paperboard

Corrugated paperboard is the most common transport packaging material in the United States (TAPPI 2001, Batelka 2000). Corrugated paper is utilized in some form or another by 90% of packaged products, and accounts for 80% of all packaging material by weight (CPA, Twede 2007). 78.95 million tons of corrugated paper was produced in 2013 (AF&PA 2014) and the industry generated $59.2 billion in revenue during 2013 alone, with growth expected to continue (Moldvay 2013).

Corrugated paperboard is a sandwich panel formed when flat sheets of paper, called liners, are glued to either side of a sinusoidal embossed medium referred to as fluting (Kirwan 2005). Corrugated flutes comes in five commonly available sizes: A, C, B, E, and F in descending order from largest to smallest (Figure 1). Several combinations of liner and medium exist that provide varying degrees of cushioning, protection, or stacking strength to a box and its contents. Single-wall (SW) board and double-wall (DW) are the most common combinations however triple-wall (TW) board, and single face (one liner and one medium) are also available (**Figure 2**).

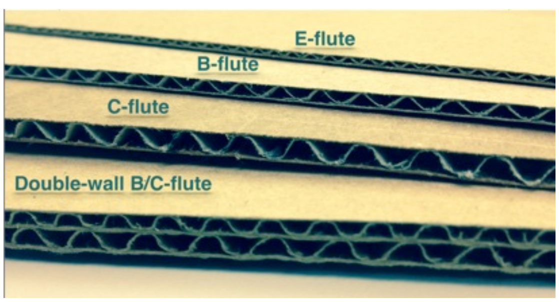

Figure 1 End view of assortment of corrugated paperboard

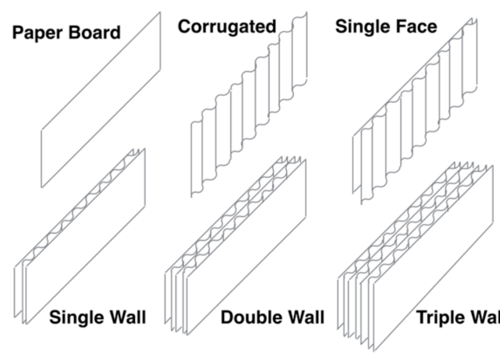

Figure 2 Various corrugated paper combinations

1.1 Development and History of Corrugated Paperboard

The original “pleated” paper patent was filed in 1856 by Edward Charles Healey and Edward Ellis Allen. The pleated paper served as a cushion between forehead and the stiff felt brim of top hats (Selke and Twede 2004). Because the paper was not implemented as a stand-alone packaging material there is some debate among scholars as to whether or not the Healey and Allen patent can be considered the ancestor of the corrugated paper we know today (Bettendorf 1946).

In the 1870’s Brooklyn New York was the hotbed of corrugated paper development. The first United States patent for corrugated paper was awarded to Albert Jones (US patent 122,023) (**Figure 3**). Bettendorf (1946) describes this new material as “the first real patent for corrugated material that is directly traceable to the present corrugated boxes”. The patent claims that the material is “corrugated, crimped, or bossed so as to present an elastic surface" and specifically states that corrugated paper presents a significant advantage in the protection of glass vials compared to the protective ability provided by tissue paper (US patent 122,023). In 1873 Albert Jones sold the intellectual property to Henry D. Norris who began producing the corrugated paper on Prince Street in Brooklyn New York (The Paper Box Maker and American Bookbinder 1909, Maltenfort 1988, Twede 2008).

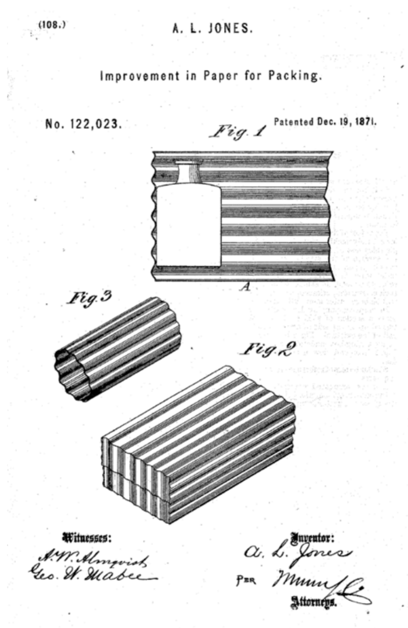

Figure 3 Image of Albert Jones original 1871 (US patent 122,023)

In 1874, Oliver Long produced and patented a material that combined the corrugation technology with a paper liner to form the first single face corrugated paperboard (US patent 9,948)(Figure 4). The liner was glued to the fluting in order to retain the shape of the flutes and prevent them from flattening out during use. By maintaining the shape the integrity of the cushioning properties would not be lost. This development caught the eye of Robert Gair who in turn purchased the intellectual property. Oliver Long produced a second patent in 1874 for a multi-ply material made of paperboard liners on both faces of a wood pulp filling (US patent 150,588) (**Figure 5**). The filler was the first of several materials used and patented by Long and was the first patent to specifically mention the application in folded boxes. However it was Robert Gair who developed the combined cut-crease machine and would go on to make corrugated boxes commercially viable (Twede, 2005)

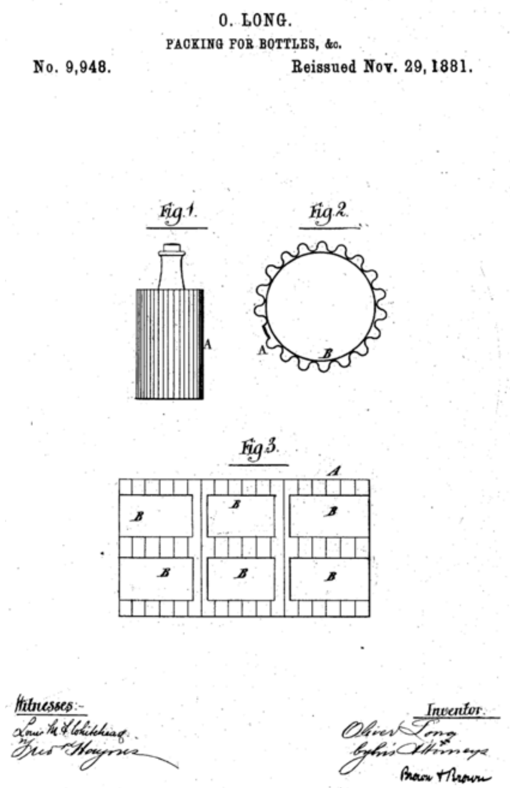

Figure 4 Single face paperboard patent developed by Oliver Long issued 1874 with Reissue 1881.

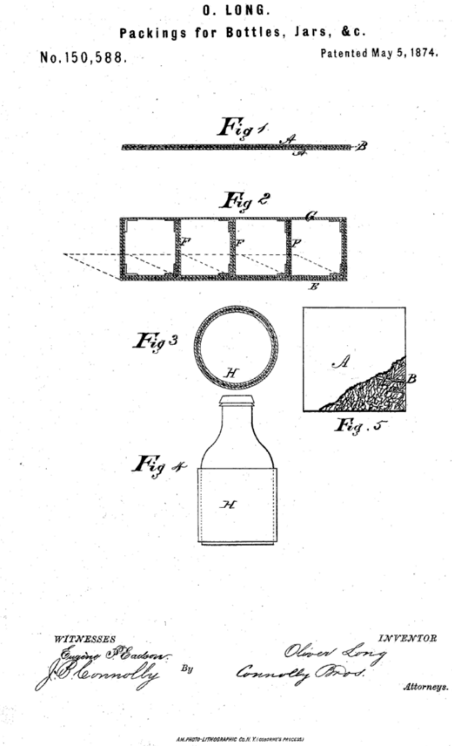

Figure 5 Oliver Long US patent 150,588 for filler material with paperboard on both faces

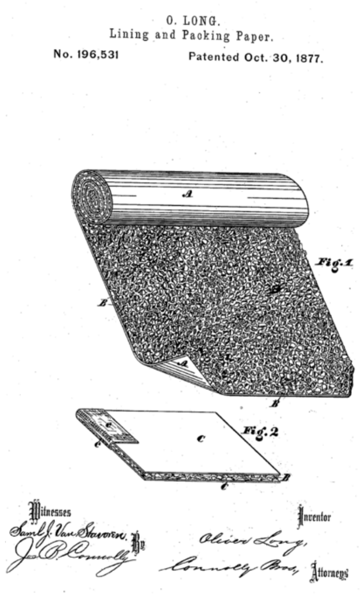

Figure 6 Cork medium with double paperboard.

In 1877, Oliver Long submitted his third patent detailing a cork medium that would be covered on both sides with a layer of paper (US patent 196,531)(**Figure 6**). This patent gained the attention of Robert H. Thompson who procured the intellectual property for his own enterprise. Robert H. Thompson then joined forces with Henry D Norris and together patented several corrugation machines (Maltenfort 1988, Twede 2007).

Lastly, in 1883, Albert Jones submitted his final material patent for an invention made "chiefly of paper or other suitable material, which can be used for window-shades, screens, wrappers, envelopes, bags, boxes, etc.". The new material consisted of a corrugated medium sandwiched between two liners; identical to todays single-wall corrugated paper (US patent 283,893) (**Figure 7**). Interestingly, Albert Jones filed his patent for use in "window shades" instead of packaging. This may be due to the fact that Robert H. Thompson owned the rights to double faced paper with "filler" and Jones' patent did not have a point of novelty. With patent security Thompson & Norris Co. thrived until the great recession, while Robert Gair Co. before eventually succumbing to consolidation pressure in the 1950's.(Zavits n.d., A Very Brief History of Piermont n.d.)

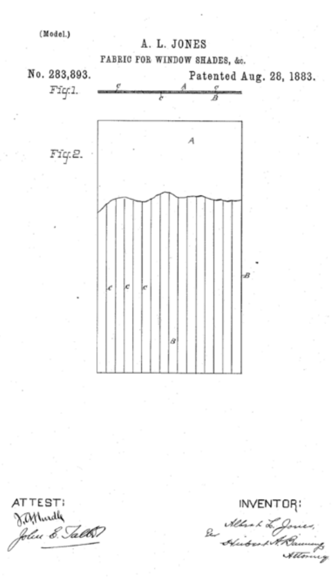

Figure 7 Albert Jones' corrugated paper patent for window shades.

1.2 Specifications of Corrugated Paperboard

Grammage (TAPPI 410), Caliper (TAPPI 411) and Flutes

It was self evident to early paper producers that increasing or decreasing the fiber content in directly impacted the strength and stiffness of paper. During the development of corrugated paperboard the paper industry was already well established and their primary measure of fiber content in a given area was "Basis weight" or grammage. Basis weight is measured in pounds per thousand square feet where as grammage is measured by the grams per square meter (TAPPI T410 and ASTM 646). Today paper is produced to standard basis weights and the choice of heavier paper directly affects the mechanical properties of the final corrugated paper. (Kellicut 1959) **Error! Reference source not found.** lists several common paper grades.

Table 1 Common paper grades used for corrugated paper liners and mediums (Soroka 2002)

Usage	Basis Weight (lbs)	Grammage (g)
Liner	26	127
	33	161
	38	186
	42	205
	69	337
Medium	26	127
	30	147
	33	161
	40	195

As **Error! Reference source not found.** indicates, the linerboard and medium do not usually consist of the same paper grade. Corrugated is specified by the grade of each layer in the order of outside liner-medium-inside liner so that a grade may be written 33-26-33. Different board weights can be combined to produce different performance characteristics. The basis weight is a measure of the constituent paper being used to produce the whole corrugated board and can be used to infer certain properties of the final product. Basis weight cannot be used to accurately calculate any mechanical properties of corrugated paper, however, heavier grades typically outperform lighter paper, assuming all other variables are equal (Maltenfort 1988).

Fluting refers to the size and shape of the sinusoidal corrugations of the paperboard medium. Some common flute sizes are shown in
Figure 1. Fluting is the largest determining factor in the caliper of corrugated paperboard and has a significant effect on all corrugated mechanical properties. Caliper measures the overall thickness of corrugated paper including the thickness of the medium and the liners and is affected by the thickness of paper and style of fluting. Caliper is important in determining the bending properties of corrugated paperboard larger calipers have a greater bending stiffness than smaller calipers (Maltenfort 1988). Caliper can be compromised during rough handling or excessive pressure during manufacturing. A collapsed or crushed flute reduces the apparent board caliper and as a result will impact the integrity of a box (Urmanbetova 2001).

1.3 Testing Methods for the Mechanical Properties of Corrugated Paperboard

The physical properties of corrugated paper do not provide enough information to accurately predict the performance of corrugated paper or corrugated boxes. Therefore, laboratory testing is the preferred way to evaluate corrugated paperboard. The following are a list of common tests and their historical development.

1.3.1 Flat Crush Testing Methods

The Flat Crush Test (FCT) directly measures the corrugated mediums ability to maintain its sinusoidal shape in the Z-axis (Figure 8). Flat crush testing values are directly influenced by the size, shape and grammage of the flutes (Kirwan 2005). Flat crush is useful when determining the cushioning properties and durability of corrugated board, however the test has seen limited application because it does not correlate well with box testing (Maltenfort 1956). Flat crush testing methods include the Concora Medium Test (TAPPI T809) and the Flat Crush Test (TAPPI T808) methodologies.

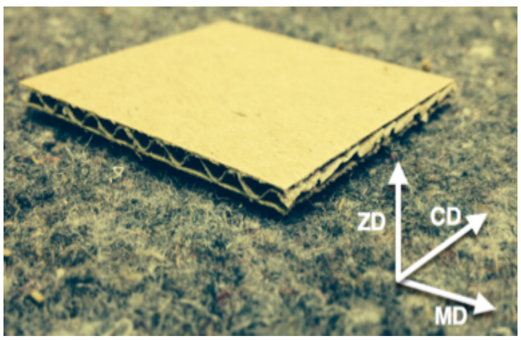

Figure 8 Sample cutting 2in x2in labeled with manufacturing orientation (Urbanik 1996)

Concora Medium Test (CMT) (TAPPI T809, ASTM D-2806) developed in 1952

The Concora Medium Test is an early flat crush testing method. Corrugated Corporation of America, or "Concora", sponsored the development of this test method. The CMT uses a 6 in. by 0.5 in. flat paperboard sample that is fluted using a hand cranked fluting die and then backed with a piece of tape to support the flutes. In essence, the tape fulfills the function of a single linerboard that holds the flute shape during testing and preventing the flutes from simply flattening out horizontally. This method of backing the sample with tape is not used in the similar Institute of Paper Chemistry Single Flute test that was developed independently around the same time (Maltenfort 1988). CMT results do not correlate with box compression testing and the complexity of set up led to inconsistent results between labs (Maltenfort 1956, Maltenfort 1988).

Flat Crush Test (TAPPI 825, ASTM D-1225)

The FCT uses a circular 10 in. test specimen to which a load is applied at 25 lbs./sec. until the flutes collapse. FCT has a distinct advantage over CMT in that the sample is produced from corrugated paperboard where as CMT required the technician to fabricate a medium by had from flat paper. FCT represents the ability of corrugated paper to maintain its sinusoidal fluting and by extension maintain the caliper of the corrugated paperboard. Caliper is an important factor in bending stiffness, which in turn contributes to overall box strength (Predicting the Compression Strength of Corrugated Boxes). As a result FCT values are an indicator of box and paper durability.

1.3.2 Mullen Burst (TAPPI 810, ASTM 2529)

In a Mullen Burst test pressure is applied to a paper sample using a pneumatic diaphragm. Pressure is increased until the sample ruptures. The result is a measure of the papers multidirectional tensile and tear strength in the Z, CD, and MD (Twede 2007, Maltenfort 1988). Like the flat crush test, it is impossible to accurately determine any stacking strength of box from the Mullen results. Never the less, Mullen Burst testing is useful as a gauge of a boxes resistance to general shipping damage (Maltenfort 1988).

The test was developed in 1887 by the textile industry and remained the most prevalent corrugated paper test in the nineteenth and early twentieth centuries. When boxes first began to supplant wooden crates the rail industry required boxes to be stamped with a minimum Mullen burst value (Twede 2007). This was beneficial because Mullen Burst has the singular distinction of providing accurate results even after shipping and handling (Maltenfort 1988). Retroactive testing has many quality assurance benefits and legal implications for customers. To this day box manufacturers are required to specify either a Mullen Burst or the Edge Crush (below) on the box in compliance with National Railroad Freight Committee's Uniform Freight Classification (UFC) rule 41. The UFC states, "A minimum of six bursts must be made, three from each side of the board, and only one burst test will be permitted to fall below the specified minimum value."

1.3.3 Edge Crush Testing Methods

Edge Crush Testing (ECT) methods are a collection of testing methodologies that evaluate the in plane compression strength of a sample in the MD and CD directions. Force is applied parallel to the plane, or perpendicular to the edge, most commonly in the CD parallel to the flutes (Figure 8). CD is the favored orientation because it tests the strength of the corrugated paper in the direction it would be oriented in a box under vertical compression. McKee et. al. 1961 found that "The edgewise compression strength of corrugated board is a dominant factor in the compression strength of a box. (McKee et. al. 1961). For this reason, heavy emphasis has been put on ECT testing as a means of predicting overall box performance.

The development of ECT testing has progressed through six main methodologies: Ring crush, Concora liner edge crush, Concora fluted edge crush, Swedish short span test, Necked Down edge crush, and what is now simply referred to as the Edge Crush Test. For comparison **Figure 9** depicts a test sample for each methodology.

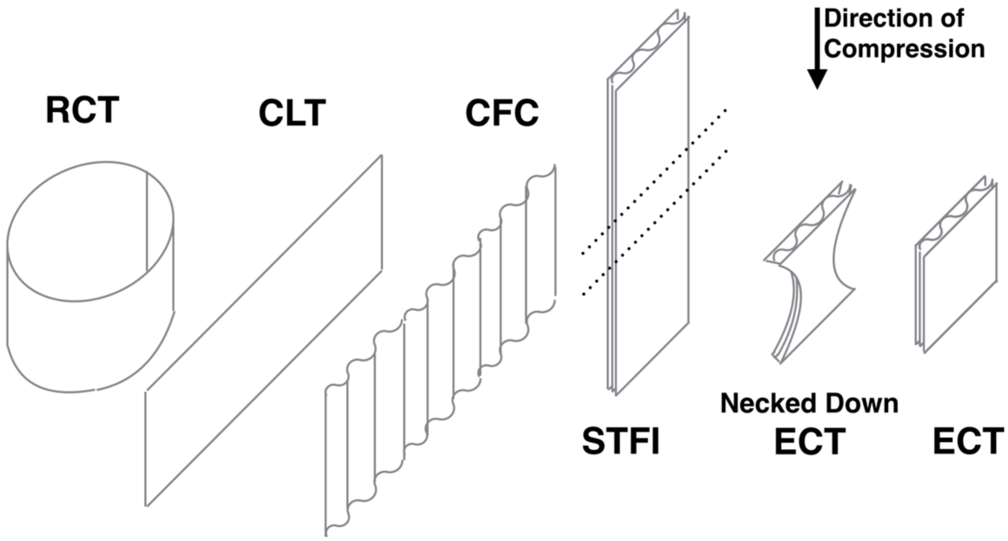

Figure 9 ECT test specimens in order of development from left to right.

1.3.3.1 Ring Crush Test (TAPPI 818, ASTM D-1164)

The Ring Crush Test (RCT) evaluates the compression and bending strength of paper. The RLT uses a 6 in. x 0.5 in. paperboard sample (not corrugated) wrapped around a circular die. The RCT fell out of favor due to large variation and poor correlation due to the annular sample inherently testing a combination of compression and bending properties (Maltenfort 1988). Maltenfort review of this testing method was less than glowing when he concluded that "[RCT] is seriously flawed as a test for reasons of principal as well as practical considerations". (Maltenfort 1988).

Data produced at Container Corporation of America (Concora) evaluated the RCT against production boxes in top-to-bottom compression and found that there was no correlation between the RCT data and the total box performance (Maltenfort 1988). This was an important finding because it invalidated several predictive models being used at the time (section 2.1.4). The corrugated paper industry has since development new and improved methods and predictive equations.

1.3.3.2 Concora Liner Edge Crush Test (CLT) (TAPPI 801)

To solve the inherent issues of the RCT, Maltenfort developed the Concora Liner Edge Crush Test while working for Container Corporation of America in the 1940s (Maltenfort 1988). The CLT uses a flat 6 in. x 0.5 in. sample of paperboard (not corrugated). The flat sample is placed in a jig to hold the sample upright. This test differs from the RCT in that the sample is not wrapped around a circular support jig but is held in a straight jig. The strait jig prevents the paper from warping or otherwise becoming misaligned. According to Maltenfort, the CLT was found to be a vast improvement over RCT; capable of producing reliable data for estimating the compression strength of boxes (Maltenfort 1988). The primary disadvantage of CLT is its susceptibility to misalignment (not perfectly parallel to compression), which negatively skewed the results. CLT has largely been replaced by methods that test the combined corrugated, consisting of both linerboards and medium together.

1.3.3.3 Concora Fluted Edge Crush Test (CFC) (TAPPI 811)

This test is a modification to the CLT where the 6 in. x 0.5 in. flat sample had been run through a hand-cranked fluting die that replicated the fluting of a corrugated medium. The sample was then tested for compression strength parallel to the flutes.
Maltenfort acknowledges that the test was originally developed to help Container Corporation of America understand the compression strength of the medium at the time when Container Corporation of America was losing market share to competitors who were utilizing new high compression strength papers and pulping techniques. The company needed a reliable test that they could use to validate new materials. A decade later Container Corporation of America ceased using the CFC and CLT in favor of Flat Crush testing because customers and legal entities were concerned with box durability. It would be another fifty years before vertical compression testing would take precedence over the Flat crush and Mullen Burst (Maltenfort 1988).

1.3.3.4 Swedish Forest Products Research Laboratory- Short Span Compressive Strength of Paperboard (TAPPI 826)

Founded in 1945 Swedish Forest Research Institute (STFI) was located in Stockholm Sweden (in 2009 they were renamed INNVENTIA). The STFI test is the first and only test to utilize a purpose built machine for conducting edge crush testing. As a result, the testing was rapid and simple, but the machinery was too costly to gain enough market penetration US paper producers (Maltenfort 1988)

The test utilized at 15mm wide by 150mm long corrugated paperboard sample. The STFI test differs from the other ECT measures in that it only tests a segment of 0.7 mm, which allows for replicate tests to be made on the same 150 mm long piece without cutting new samples. The STFI test produces results that correlate to half the basis weight of the corrugated board, which suggests that the additional fiber has a dimension return in edgewise strength (Fibre Box Handbook 2005). Overall it was shown that the STFI testing machine has a good correlation other the Edge Crush Testing method (R^2= 0.97) (Whitsitt 1985).

Edgewise Compressive strength of Corrugated Board -Short Column Test (ECT) (TAPPI 811 waxed edge/838 neckdown/839 clamp, ASTM D-2808)

In the early 1900s, corrugated paper suppliers made a unified push into the rail industry by way of Uniform Freight Classification (UFC) Rule 41 and eventually gained favor in the trucking industry regulations with National Motor Freight Classification Item 222 (Urbanik 2006). The cereal foods industry became a strong driver of corrugated paper use and corrugated packaging continued to expand due to its comparatively low weight, low cost, and ease of assembly (Twede 2007, Kellicut 1958). During this time the Mullen Burst test was the primary corrugated paper test and was required on the Box Manufacturing Certificate (BMC) (Rule 41 for rail and Item 222 for trucks) (**Figure 10**).

The modern wooden pallet was developed during World War II and became more prevalent in transportation and packaging industry after the war. Unitized boxes on pallets were not exposed to the same shipping and handling stresses that were experienced by individual boxes, which shifted the design concern toward vertical stacking strength (Goodshall 1968). A new test was needed to verify stacking strength because the Mullen burst did not correlate with box compression strength making it insufficient for the specification of warehouse-stacked materials (McKinlay 1960).

Figure 10 Box Manufacturers Certificate with ECT and Company name prominently stated

The Edge Crush Test (ECT) (TAPPI T811) was developed as a way to directly measure a corrugated paper sample in the Cross Direction (parallel to the flutes). ECT testing produced several failure modes with the ideal test encouraging the corrugated paper to crush at the center of the test specimen. Unfortunately this result is difficult to achieve and many samples buckle or curl where the paper contacts the loading platens. Kellicut 1951 and McKinlay 1960 experimented with several sample sizes. For example McKinlay utilized samples of 4 in. x 1 in. which are still specified by ISO 13821 and 3037 compared to the far more prominent 2 in. x 2 in. samples used by TAPPI standards (McKinlay 1960). McKee et. al. presented a new “necked down” method in his 1961 research paper after extensive study of the waxed edge method. The study claimed that the necked down column test “would not suffer from the shortcomings of edge failure of the specimen” (McKee et. al. 1961). To help drive failure to the center of the specimen he cut circles from each side of the sample to produce and hourglass shape which he referred to as necking-down (**Figure 9**). The new method was effective but time consuming and suffered from high variability between technicians who were struggled to cut the necked-down circles consistently (Koning 1965). Koning compared the necked-down compression test with a simplified 2 in. by 1.25 in. rectangular specimen with wax dipped ends and found that the two preparations were statistically identical. Koning concluded that the rectangular sample was the preferred method due to the minimal cutting time and reduced variability compared to the necked down version (Koning 1965). Konings method became the TAPPI 811 method that is still preferred today.

After several decades of development, the ECT test had been verified to such an extent that in 1990 the Unified Freight Classification (UFC) was revised to accept the test procedure in addition to the Mullen Burst Test. Effective in 1991, the new standard allowed box manufacturers to use either the Mullen Burst test or ECT on their Box Manufacturers Certificate (Soroka 2002). The UFC requires “A minimum of six tests must be made and only one test is permitted to fall below the specified minimum value, and that one test cannot fall below the specified minimum value by more than 10%.”

Since Koning’s 1965 research, little has changed in the methodology of ECT testing with the exception of TAPPI T 839 developed at Weyerhaeuser. The method allows for the use of a clamping mechanism that eliminates the need for dipping the specimens in paraffin wax. Richard Morris developed the new clamping mechanism while he was employed at (Maltenford 1988). The new method reduced sample preparation time while at the same time the coefficient of variability decreased from 5.5% to 3.9% however test results are statisticaly higher than T811 tests (Whitsitt and Schrampfer 1988). To date the clamp method is not officially accepted by the UFC (frank 2003)

1.3.3.5 Comparison on ECT and Mullen Burst

Corrugated paperboard is an orthotropic material; therefore strong consideration must be taken when evaluating what properties will produce a successful package and not a wasteful one. It is worth noting that Mullen Burst values and ECT values are not mutually exclusive. The merits of ECT and Mullen Burst have been compared on several occasions including Maltenfort 1988 and McSweeny 1993. As stated previously, Mullen burst is a multi-directional test that is heavily dependent on basis weight of the constituent paperboard and is a strong indicator of total box durability where as ECT is the most prominent factor responsible the vertical stacking strength of a box. A box that is specified by ECT testing however, allows the manufacturer to focus their efforts on optimizing the material for vertical stacking strength such as optimized fiber orientation. As a result the manufacturer can reduce overall fiber content in vertical stacking situations (Allaway 2005). Products that are stacked for long periods or shipped in unitized loads will benefit from board specification based by the ECT test. It has been found that the specification of corrugated board based on ECT instead of Mullen Burst testing may result in 4.3% cost reduction and 17.5% reduction in paper material (McSweeney 1993).

Less than Truck Load (LTL) shipping environments subject packages to impacts and compression loads in more than just the vertical direction. LTL shipments and parcel deliveries are known to be far more severe than a dedicated truck load and companies whose products that are subjected to these much rougher conditions should consider specifying their board based on the Mullen Burst test (Longtin 2003).

1.3.4 Bending Stiffness (TAPPI 820, ISO 5628)

Bending stiffness is a measure of flexural stiffness in a panel. Samples 1 to 2 in. wide and a minimum of 6 in. long are supported in a four point bending jig (**Figure 11**). ISO specifies minimum length based on board thickness and does not recommend a particular sample width. Research by McKee et. al. 1962 indicates that three-point bending is a comparatively poor test for corrugated paper due to the fact that a single concentration of force will crease the paper causing immediate failure and producing limited value (McKee et. al. 1962). Lee and Park 2004 confirmed that four-point bending is the preferred method for testing the flexural stiffness of corrugated paper because it minimizes sheer stress in the area being tested. (Lee and Park 2004). Lee and Park chose to use samples of corrugated 500 mm. x 50 mm. for their research.

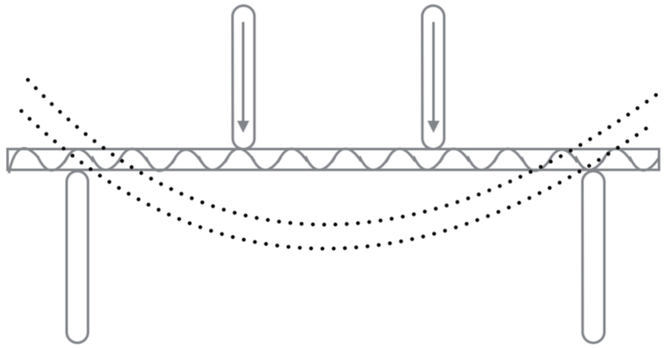

Figure 11 Four point bending diagram. Dotted lines represent a sample bending during testing.

Larger flutes provide a deeper beam that is more resistant to bending so increasing the combined board caliper directly correlate to increases in flexural stiffness. As the sample bends during testing the linerboard on the convex side experiences tension while the inside board experiences compression. McKee concludes that board caliper and liner stiffness are the primary factors influencing bending stiffness and this finding confirmed by M.E. Biancolini (2004) using finite element models (section 1.3.7). Machine direction (MD) usually has a greater bending stiffness CD bending stiffness by 29–48% due to the liner's superior strength in MD. (McKee et. al. 1962, Lee and Park 2004).

In 1964, the combined team of Buchana, Draper and Teague worked to confirm and solidify McKee et. al.'s findings through a more extensive battery of tests. The team found that corrugated bending stiffness correlated with box compression strength. Increasing corrugated paper bending stiffness resulted in increased box compression strength however continual increases produced diminishing returns in overall box compression. (Buchanan et al. 1964). This finding would play a crucial roll in McKee's later work where he developed a formula to predict box compression strength (section 2.1.4).

1.3.5 Puncture Testing (TAPPI 803, ASTM D-781)

Puncture testing utilizes a weighted pyramid, known as a puncture head, which hangs from a pendulum arm that is released from a fixed distance whereby it swings into the paper. It has been suggested by early studies that puncture testing correlates well with overall box compression among other physical properties; however, it has been repeatedly proven that puncture testing is inaccurate and inconsistent, while lacking in correlation (McKee et. al. 1964, Buchanan 1964). A primary concern is that puncture testing does not isolate one physical property (McKee et. al. 1964). Maltenfort simply concludes "such a test is not suitable as a basis for a specification, and cannot be accepted as a standard" (Maltenfort 1959). However, the Uniform Freight Classification still accepts puncture testing as a valid means of ensuring box integrity. The testing regimen set forth by the UFC is as follows, "A minimum of four puncture tests must be made and only one puncture test will be permitted to fall below the specified minimum value". More information on the intricacies of the puncture test and comparison of McKee et. al. and Maltenfort's work can be found in "Performance and Evaluation of Shipping Containers" page 398 Chapter 49 in the footnotes.

1.3.6 Miscellaneous Testing

Over the years additional tests have been developed to better understand the different properties of corrugated paper in the machine and cross directions including but not limited to: Taber stiffness test (TAPPI T489), tensile testing (TAPPI T494), tear testing, Cobb, and shear testing (Nordstrad 1994). Each of these tests serves a function for a variety of industrial needs, some even correlate well with the previously mentioned tests but they are less common and do not readily apply to the understanding of box strength.

1.3.7 Finite Element Method

With the development of the personal computer new efforts were made in modeling the complex interactions occurring within the layers of corrugated paperboard. Finite Element Analysis (FEA) is a computational methodology that reduces complex structures into many simplified elements. Forces can be applied to the larger structure and evaluated at each simple element in order to understand the performance of the cohesive structure. Finite Element Models (FEMs) are tested against real world specimens to confirm their accuracy. Currently, FEA is used for complex engineering environments such as structural engineering. These modeling techniques have yet to become ubiquitous in the broader packaging industry due to cost and complexity associated with modeling cheap and highly variable materials (section 1.4 below). As a result FEA of corrugated boxes does not have the same payback in cost, design, and safety that is associated with the modeling of bridges, buildings and aircraft.

1.4 Factors Affecting the Mechanical Properties of Corrugated Board

Factors that readily affect ECT and stacking strength can be sorted into two main categories: material variations and environmental conditions. Material variations are those qualities intrinsic to the paperboard as it was manufactured, such as board grade, geometry, and production variation. Environmental factors are those that the paper may experience during its life cycle such as humidity, stacking patterns, and air pollutants. Environmental factors are not inherent to the box and are typically mitigated through the application safety factors.

1.4.1 Material Variation

Basis Weight

Kellicut and Maltenfort independently demonstrated that an increase in fiber content, and thus basis weight, correlates to a stronger paper in all tests (Kellicut 1959, Maltenfort 1959). Cutshall (1990) found variation in paper basis weight occurred in MD, CD and ZD simultaneously and at multiple frequencies along the paper. Cutshall is clear to point out that “variation is natural” and a packaging engineer should expect variation in cellulose-based materials. The DOT lists acceptable variation of corrugated basis weight at +/-5% when packaging selective HAZMAT materials (Department of Transportation 2014).

Fluting

Flute size (largely determines caliper) and flute geometry are the most significant factor affecting board properties, assuming the constituent paper basis weight is held constant (McKee et. al. 1963). Both amplitude and wavelength of the fluting contribute to the physical properties of a given shape. Flutes of higher amplitude have greater bending strength (McKee et. al. 1963). Flutes have been consolidated into five main sizes. A, B, and C flutes were the original three available followed by the much smaller E and F flutes which benefit from increased printability (Fiber Box Handbook 2005).

The wavelengths of the flutes directly influence the amount of medium available for structural support, which influences the printability and finish quality of paper. The corrugated industry defines the number of waves per linear foot of linerboard as “flutes per foot”. Another useful factor for corrugated manufacturing is the “Take up factor”, defined as the linear feet of medium divided by the linear feet of liner board needed to produce a specific flute type. Take up factor is directly related to flute size and shape (Urbanik 2001).

Printing

Kawanishi 1988 found that printing process could affect the compression strength of a box. The printing process requires contact between printing rollers and the corrugated paper thus some force is applied in the Z-axis and inevitable causing a small amount of flute collapse. Kawanishi (1988) found that the printing methods of his decade could reduce compression strength by as much as 27%, however, modern printing techniques have significantly reduced this detrimental effect by reducing the pressure needed to transfer the ink(Twede 2007).

Adhesive Application

A variety of adhesives in various application thicknesses are used to bind the liners and medium together to form corrugated paperboard. Popil et al. 2007 found that increases in the thickness of application thickness increase the ECT of the corrugated board. Additionally, the study indicates that excessive adhesive application will warp the final product. Propil’s study also found that various adhesive chemistries (PVA, starch, acrylic, etc) affect the ECT strength (Propil 2007).

Recycling

Recycling rates in the US have increased with 29 million tons of paper reentering the paper stream, 50 percent of which went into makeing new corrugated paper.(CPA 2013). It is not uncommon to see boxes made of 100% recycled paper but most contain around 35% (TAPPI 2001). Wood fiber degrades with each pass through the recycling stream decreasing its physical properties. Eight passes can reduce Mullen Burst strength 50% (Kirwan 2005). However, an extensive survey of recycled board and noted that production grade recycled paper had a greater thickness and higher burst strength due to the additional material required to maintain a specified ECT. (Zhoa 1993) Recycled fibers increase the standard deviation of ECT testing thus increased basis weight is required to achieve the same ECT strength compared to virgin fibers. (Almanza et. al. 1993).

Testing of formed boxes produced found that “Recycled boxes were approximately 5.8% stronger in vertical compression strength than virgin boxes”, this is likely due to the extra material required to maintain a 32 ECT paper (Zhoa 1993). During testing it was also found that recycled boxes were more sensitive to high relative humilities. At 91% RH the recycled boxes lost approximately 50% of their compression strength where as the virgin board lost only 43% compression strength (Zhoa 1993).

1.4.2 Environmental Variations

Moisture Content (TAPPI 412, ASTM D-644)

Moisture content is a critical factor determining paperboard strength and can be calculated using Equation 1.

Equation 1

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

Where $W_1 =$ Sample weight before drying

$W_2 =$ Sample weight after drying

Moisture content has a dramatically negative effect on the physical properties of paper. Bandyopadhyay et. al showed that paper moisture content begins to change the moment it is exposed to a different relative humidity and the rate of moisture sorption is dependent on the speed and magnitude of change in relative humidity (Bandyopadhyay et. al. 2000). Relative humidity in the environment has a non-nonlinear relation to the moisture content of corrugated paper. Furthermore, paper exhibits a phenomenon called hysteresis where the equilibrium moisture content is dependent on its previous moisture content. For example, if one paper sample is preconditioned at 20% and a second is preconditioned to 80%, then they are both conditioned to 50% relative humilities their finial moisture content will be lower and higher, respectively. For this reason ASTM 4332 "*Practice for Conditioning Paper and Paper Products for Testing"*, requires the samples to be preconditioned at 20-40 C° and 10-35% relative humidity before being raised to the ASTM standard of 23±1 C° and 50±2 % relative humidity.

In addition to affecting paper strength and stiffness, changes in moisture content produce swelling and shrinking in the fibers. This dimensional variability caused by moisture content is known as hygroexpansivness (Soroka 2002). Corrugated paper dimensions can vary up to 0.8% in the MD and 1.6% in the CD (Soroka 2002). During absorption and desorption the paper may warp when the hygroexpansivness is uniform (Soroka 2002).

2 Corrugated Boxes

2.1 Development and History

In 1875, Albert Jones, inventor of the corrugated paperboard, introduced the first precut box (US patent 163,379) (

Figure 12). Jones' invention was novel in the sense that the size and box was creased and cut to particular shape at the factory. This development was the first step in the evolution of manufacturing corrugated boxes.

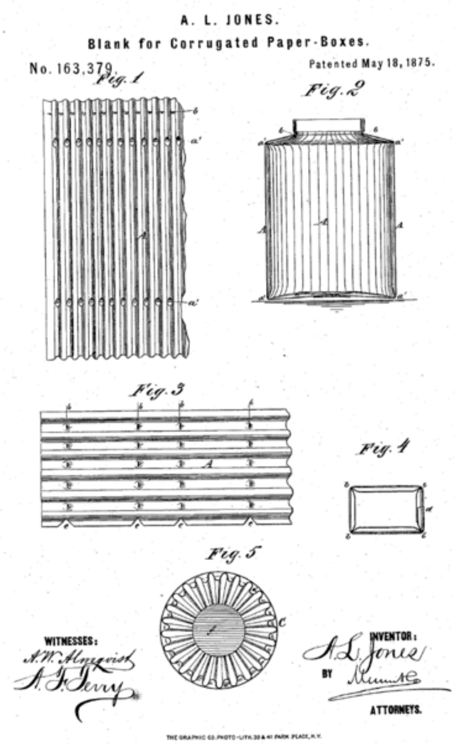

Figure 12 Albert Jones single face corrugated paper patent

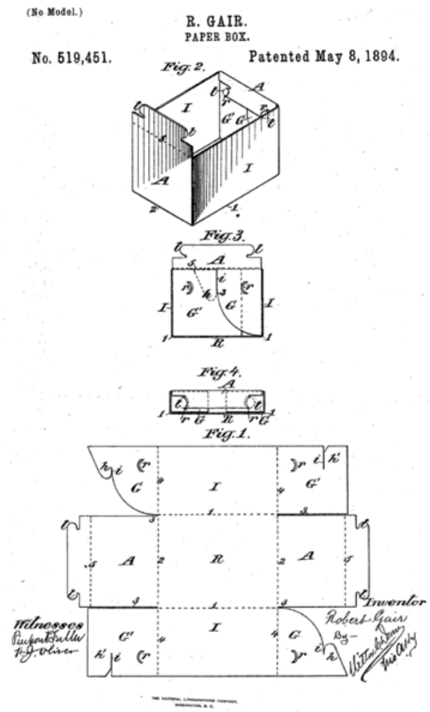

Figure 13 Robert Gair's patent for folding paper box

Rober Gair submitted the first patents that specifically outline designs for folding boxes in 1894 and 1899 (US patent 519,451 and 619,475) (**Figure 13**). By 1905 corrugated board still remained stiff and cumbersome to handle. This inspired George Swift to invent a scoring device that allowed for boxes to be folded easily along a strait line (Twede 2007). By the early twentieth century, Robert Gair, Robert H. Thompson, and Henry D. Norris had merged their three corrugated paper and box plants into a cartel. Thompson and Norris developed the first Regular Slotted Container (RSC) around 1914 (Twede 2007). RSCs gained popularity for their simplicity, machinability and materials savings that are inherent to their equal flap length design. (Maskell 1986)

2.1.1 Corrugated Box Properties

Design

The primary function of a corrugated box is to protect, store, advertise, contain, and transport goods. Over the years many styles of corrugated box have developed and the European Federation of Corrugated Board Manufacturers (FEFCO) has standardized many of these designs. The regular slotted container, FEFCO code 201, is by far the most prevalent corrugated box style (Twede 2007).

Stacking Strength

1903 was the first year in which corrugated boxes were transported by rail. However, as demand grew for shipping products in corrugated paper grew the rail industry applied a 400% in sure charges that was not equally applied to wooden crates (Twede 2007). These additional charges were due in part to the rail industry protecting its horizontal integration of timber production for rail ties and wooden crates (Twede 2007). In 1914, the Interstate Commerce Commission ruled against the price discrimination by the rail industry and within ten years corrugated boxes moved more freight via train than wooden crates.

Several factors came to a head in the 1950's and 60's that led to stacking strength becoming the primary focus for packaging designers. Firstly, the National Interstate and Defense Highways Act (Public Law 84-627) was approved in 1957. This act lead to the interstate system which opened up commerce by truck. Secondly, the railroad companies lobbied for higher taxes to be levied on their competitors while simultaneously increasing rail freight rates to increase profits (Weingroff 2013, Twede 2007). These two factors alone led to an explosion in full truck load (TL) shipping, opposed to rail or less-than-truckload (LTL). Third, Fordrainer Kraft Board was introduced. This new type of paper provided a strong, easy to manufacture, and cheaper option for both suppliers and customers compared to the standard wooden crates or jute fiber boxes (Twede 2007). Lastly, wooden pallets and fork lifts had been developed by the military during World War II allowing for boxes to be combined into a single load with a single destination, which limited the handling required in an LTL system. (LeBlanc 2003). When these factors were combined, TL shipping became the obvious choice for companies trying to move their products in bulk at a fair rate directly to its destination. Combining boxes into unit loads for TL shipping resulted in fewer impacts and less intense shocks resulting from drops compared to LTL shipment (Ostream and Godshall 1979). The use of trucks also eliminated the severe horizontal shocks that products receive when train cars are coupled in switching yards (Ostream and Godshall 1979).

With the adoption of truck shipments, vertical vibration during trucking became the primary cause of damage. Boxes have since been optimized for vertical strength and as a result, vertical box compression has become the critical design focus.

2.1.2 Measuring the Compression Strength of Corrugated Boxes

2.1.3 Testing Methodology

ASTM International (ASTM) D-642 "Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads" is the standard used to determine compression strength of a box. The test is straight forward but there are several considerations that should be taken into account when testing boxes. These include platen type, rate of loading, box location and paper conditioning.

Comparison of Fixed and Floating Platen

ASTM and TAPPI standards specify a fixed platen test setup where the plates used for compression are fixed exactly parallel to each other. It is also possible to test using a moving platen environment where one platen (usually the top) is allowed to pivot on a ball joint. Langlois (1989) found that floating platen tests resulted in lower compression strength compared to fixed platens. Singh et al. (2007) found that when testing with a floating platen it is imperative to place the box directly in the center of the pivot. If placement is not exact the compression strength drops and the deflection increases proportionally to the offset from center (Singh 2007).

Rate of Compression

ASTM D642 "Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads" designates a compression rate of 0.5 in./min. Varying the platen compression speed from 0.1 in./min. up to 1 in./min. has shown no significant effect on the box compressions strength. (Singh 2007)

Location on Compression Table

A box will lose up to 15.8% of its measured compression strength when it is moved away from the center of a fixed platen Lansmont Model 152-30 compression table (Singh 2007). Additionally, box deflection increases as the distance from the center of the table increases.

Conditioning of Corrugated Boxes

As mentioned previously, moisture content has a significant affect on the compression strength of corrugated boxes. ASTM D4332 "Practice for Conditioning Paper and Paper Products for Testing" list the many different options for conditioning such as cryogenic, frozen food storage, tropical and desert conditions. By far the most prevalent is the "Standard Conditioning Atmosphere" of 23±1 °C (73.4±2°F) and 50±2% relative humidity for 72 hr. prior to testing. Special care should be taken to precondition the boxes at 20 to 40°C (68 to 104°F) and 10 to 35 % relative humidity. Preconditioning is essential for consistency due to hysteresis (Frank 2013).

2.1.4 Predicting the Compression Strength of Corrugated Boxes

Practical Approaches

One of the most influential packaging research organizations was the Institute for Paper Science and Technology founded in Appleton Wisconsin in 1929. Prior to the development of adequate box testing methods, early designers were known for testing packages by simply tossing them down the stairs (McKee et. al. 1957). Sometime around the 1920s, the first box compression testing began but the data was not recorded or kept (McKee et. al. 1957). Once reliable compression testing methods had been established research began to focus on developing a predictive model for box compression strength. At the time it was generally recognized that the strength of a box correlates with the properties of the corrugated paper it was made from, therefore it should be possible to develop a predictive equation that would allow for quicker development of new cases while reducing the chance of "over-packaging".

In 1956 George Maltenfort conducted the first comprehensive study of corrugated box compression strength while he was at Container Corporation of America. The goal of the study was to produce a usable equation that would allow industry to predict the compression strength of corrugated boxes. It is worth noting the Maltenfort's equation is only useful for C-flute RSC style corrugated boxes. After testing of various box sizes he developed the following equation for top-to-bottom box compression. (Equation 2)

Equation 2

$$\text{Top-to-Bottom Compression} = 469 + (5.8 \times Length) + (12 \times Width) - (2.1 \times Depth)$$

In 1957, while at the Institute for Paper Science and Technology, R.C. McKee and J.W. Gander published their first study of box compression strength. Firstly, they established that 90% of box's overall deflection can be directly attributed to the flaps and score lines, and not to the vertical walls (McKee et. al. 1957). Secondly, their research found that the failure of a box is triggered by the failure of the paper at or near a corner. They concluded that the four corners support the majority of the load. This finding is important for the understanding of what constitutes the "failure" of a box. (McKee et. al. 1957). Third, McKee et. al. demonstrated that a box, with its flaps completely removed (referred to as a tube), has higher compression strength than a box with flaps intact, assuming both have equal board grade and dimensions (McKee et. al. 1957). These findings would provide the background for McKee's influential later.

Plate Theory Approaches

The following year (1958) at the USDA Forest Products Laboratory, Kellicut and Landt developed the first formula that would predict the compression strength of a box based on the properties of its paper components. The formula they developed was based on previous studies that evaluated the plate buckling of plywood. This paper is significant for being the first to evaluate box sidewalls as if they were thin plates that follow traditional plate buckling theories.

During the testing, the team evaluated the merits of multiple laboratory tests including; the 4 in. by 1 in. "strip column test" (ISO 3037), a precursor to the smaller ECT, along with bending stiffness, shear strength, flexural shear and tensile strength. Ultimately the team chose to derive box compression strength from the "composite" Ring Crush Test. The "composite" refers to a methodology where the medium and both paperboard liners are tested independently and the results summed into one data point. To compensate for flute size and manufacturing method the equation used an empirical "Box Factor" denoted as J in the equation (Kellicut and Landt 1958). The formula Kellicut and Landt produced in shown below (Equation 3). In their conclusion Kellicut and Landt noted the accuracy of the equation was limited by multiple constants, and utilization of the inconsistent ring crush test (Kellicut and Landt 1958).

Equation 3

$$P = P_x \left(\frac{a_x 2^2}{\left(\frac{Z}{4}\right)^2} \right)^{\frac{1}{3}} ZJ$$

Where

$P =$ Compressive strength of box in pounds

$P_x =$ Compsite Ring Crush load of built up board

$a_x 2$= Either 8.36; 5.00, or 6.10 for A-, B- or C-Flute, respectively

Z= Perimiter of box in inches

J= Box factor

In 1960 A.E. Ranger of the Bowater Research and Development Company published an equation that modeled the box sidewall as a strut or thin column. McKee et. al. initially concluded that a box does not support a load evenly around its perimeter. Ranger agreed with McKee' s findings and developed the following equation (Equation 4) to model the amount of pressure a box supported at any given point along its perimeter.

Equation 4

$$P = (P_A - S)\left\{ \frac{ad}{as+1} + g\left(\frac{4x^2}{l^2}\right)^{(bl/d+1)} \right\} + S...$$

Where:

$P =$ total linear pressure at any point along the edge

$P_A =$ average value of P

$S =$ critial linear pressure for a simple strut of the same board

$l =$ total length of panel

$x =$ distance of the point considered the mid-point of the edge

$d =$ height of panel

a,g and b are constants

Ranger conducted a series of experiments that found the vertical compression strength of a panel to be non-linear across its span, and the corners of the box support the majority of top-to-bottom compression. And therefore, panel compression strength should be subject to a combination of vertical and flexural stiffness. At the time it was well established that the perimeter of the box is the primary driver of compression strength. Ranger theorized that a box could be modeled as a series of independent panels where each would have their own buckling constant and compression strength. Unfortunately, Ranger's work was also hindered by the limitations of the ring crush test (Equation 5).

Equation 5

$$W = \frac{2l(5Cd^2 + 2Sl^2)}{5d^2 + 2l^2} + \frac{2w(5Cd^2 + 2Sw^2)}{5d^2 + 2w^2}$$

Where:

W = the maxium load

$$C = 1.5R_2 + 0.72(R_1 + R_1')$$

Where:

R_2 = ring stiffness/in of the fluted medium

R_1 = ring stiffness/in of the first liner

R_1' = ring stiffness/in of the second liner

Ranger made a great stride by applying sound engineering logic in his formula, however the equation was ultimately encumbered by his modified version of the ring crush test denoted in equation 5 with the letter "C". A comparison of theoretical to actual results was limited to +/-10% accuracy. In the conclusion Ranger notes the poor correlation of RCT and suggests that bending stiffness could be a preferred testing method of the constituent paper. (Maltenfort 1988)

In 1963, McKee, Gander and Wachuta continued to develop a general model for predicating box compression strength. By moving away from ring crush testing once and for all and utilizing a combination of ECT and bending strength in one formula the McKee formula has become the go to equation in the packaging industry (Maltenfort 1988). The following is a brief overview that will high light some of the assumptions made by McKee et. al.

The first assumption was that the compression strength of a box can be estimated by summing the theoretical compression strength of each panel (Ranger 1960, McKee 1963). A basic formula for plate compression strength was used as the theoretical foundation (Equation 6). McKee rearranged the variables and substituted the appropriate corrugated box properties into the equation. P_m effectively became ECT and P_{cr} became the CD and MD bending strength of the panel and the box perimeter (Equation 7).

Equation 6

$$P = c\left(\frac{P_m}{P_{cr}}\right)^b$$

P = ultimate strength of the plate per unit width (lbs./in.)

P_m = edgewise compression strength of plate material (lbs./in.)

P_{cr} = instability load (lbs./in.)

c, b = constants

Equation 7

$$P = aP_m^b\left(\sqrt{D_x D_y}\right)^{1-b} Z^{2b-1}$$

Where

P = Total box load pounds

P_m = Edgewise compression strength of combined board, Lb/in

D_x = In-machine flexural stiffness of combined board, Lb.-in.

D_y = Cross-machine flexural stiffness of combined board, Lb.-in.

Z= Perimiter of box in inches

a, b= emperical constants

Transitioning from P_{cr} to CD and MD bending strength was an in-depth theoretical process based on information gathered from NASA's research into the buckling theory of engineered wood panels and crates (Noris 1942, Buchanan 1964). **Figure 14** contains several equations used to calculate P_{cr}. To calculate P_{cr} McKee determined the boundary conditions of the sidewall to be fixed at the top and bottom while the vertical edges are pinned (illustrated in top right diagram of **Figure 14**). Lastly, McKee set the buckling coefficient (k) at 0.5 based on previous studies (McKee 1963).

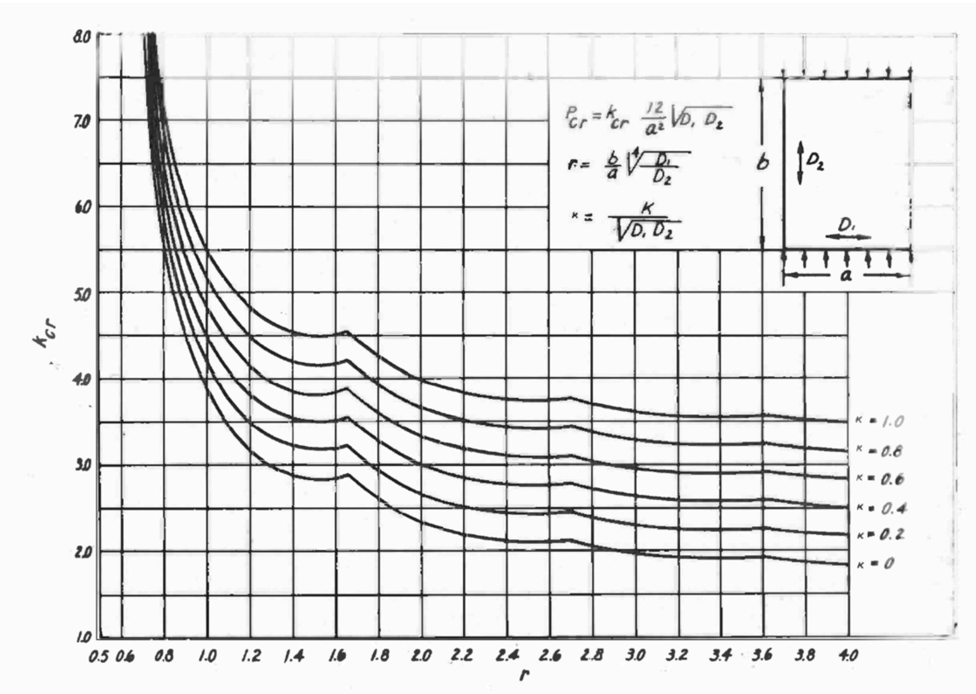

Figure 14 K_{cr}/r chart by March 1962 showing the scalloped relationship between the aspect/flexural ratio (*r)* and the buckling coefficient K_{cr}

The only difference between the width and length panels of a given box is their aspect ratio (panel depth/ panel width). This aspect ratio (r) determines the coefficient of buckling (K_{cr}) and thus P_{cr}, when the other material factors are identical. For ease of use McKee simplified the equations of March (1962) using several key variable including the buckling coefficient K_{cr}. Roughly speaking, K_{cr} is the product of the buckling constant (K) and the combination of aspect ratio with bending stiffness designated as (*r*) (**Figure 14**). McKee simplified the equation so that P_{cr} became the CD and MD bending strength of the panel multiplied by the box perimeter (Equation 7).

The final step in the simplification process was to determine the value of constants. This was accomplished by testing and calculating generalized values to replace the constants *a* and *b* with the empirical *a*=2.028 and *b*= 0.746 (Equation 8).

Equation 8

$$P = 2.028\ P_m^{0.7546}\left(\sqrt{D_x D_y}\right)^{0.254} Z^{0.492}$$

Two years later, McKee et. al. updated his formula (Equation 8) for RSCs to produce a redacted version for industry use (Equation 9). Maltenfort provides an in depth evaluation of the formula noting that "The formula… was recognized as being in need of simplification if it was to find wide use in commercial practice, not least for the reason that few laboratories were equipped to generate flexural stiffness data." (Maltenfort 1988).

McKee made two final changes to the equation. First, the exponents were rounded to their nearest root for, example 0.492 was simplified to 0.5. And second, bending stiffness was determined to be difficult for a typical user determine without the proper testing equipment. Previous studies of bending stiffness found a linear relationship with board caliper so the square root of D_xD_y was replaced with board caliper (h). The primary advantage of using caliper is that it can be easily measure or ascertained from the flute size. This simplified formula (Equation 9) is commonly referred to as the "McKee Equation" and is still used widely today. The equation is highly accessible because it only requires knowledge of the box perimeter (z), caliper (h) and ECT value (P_m) all of which can be determined from a box design and a box manufacturer's certificate.

Equation 9

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

Where:

P = compression strength (lbs.)

P_m = edge wise compression strength of combined board (lbs./in.)

h = combined board caliper (in.)

Z = perimiter of box (in.)

The results of McKee's simplification process came at the cost of accuracy. The simplified equation was found to over estimate box compression strength for A, C and B flutes by 4.6%, 7.4% and 8.5%, respectively and was 0.4% less accurate than the full version (Equation 7) at predicting box compression (McKee et. al. 1963). Additionally Equation 9 can predict +/-15% for 95% of the data compared to 97% for Equation 7. Box designers should be aware that Equation 8 and Equation 9 are limited to boxes with a perimeter between 30 and 135 in. and having sidewalls tall enough to avoid short column crushing.

The year after publication of McKee et. al.'s standard setting equation, Buchanan, Draper and Teague drew up a version that was further simplified (Equation 10). This three-man team investigated McKee's findings by conducting a larger range of tests on a smaller number of box variables.

Equation 10

$$K = CE^{3/4}D^{1/4}$$

Where

K = compression strength per inch of perimeter

C = flute constant (can be simplified to 0.57)

E = ECT in lb/in

D = CD bending stiffness in in^2lb/in

The team is careful to point out the similarities their equation has with McKee yet cite some differences. Firstly, they have eliminated caliper from the equation. Secondly, the equation was simplified to only include bending stiffness in the vertical directions as they found cross directional bending to be insignificant. This simplification is supported by the conclusion that "the combination of end-crush and bending stiffness has the best correlation to compression." (Buchanan 1964). All testing was performed on 10 in. tall tubes (boxes without flaps) so correlation of this data to real world boxes may not be ideal.

In 1988, Kawanishi conducted a comprehensive evaluation of all the corrugated test methods including Mullen and ECT. Kawanishi concluded that more extensive testing and computer modeling could accurately predict box compression strength in a manner that was easy to use for his company's procurement department. The study and its equation incorporated moisture content, printing variations and box type. Most importantly, Kawanishi's equation does not require any laboratory testing on the part of the user due to the elimination of flexural stiffness and ECT (Equation 11). All factors have been built directly into the formula so that any purchasing department could calculate the necessary information from the basis weight specifications and liner specification.

Equation 11

$$F = 3.79 \times 10^{-8} \times K^{0.379} \times W^{0.65} \times w^{1.2} \times d^{-4.15} \times y^{2.45} \times t^{3.43} \times Z^{0.565} \times k^{-0.315} \times P^{0.0602} \times S^{-1.1}$$

Where

F = Compression strength

K = Liner type (2 for B-flute)

W = Total basis weight of linerboard (g/m^2)

w = Total basis weight of corrugated medium (g/m^2)

d = Total corrugateion ratio (1.36 fir B-flute)

y= Average corrugated count (50 for B-flute)

t= Thickness of corrugated fibrevoard sheet (mm)

Z= Perimiter of box (cm)

k= Type of box (1 for RSC, 2 for Wrap around)

P= Printed ratio of bo (1 for no print, 0.01 for solid pring)

S= Moisture content of side wall

Attempts to Improve Prediction Accuracy

Hann et. al. began a series of experiment in 1991 to evaluate the edge compression strength of 25 mm x 100 mm corrugated paper panels in order to better understand box compression strength of a box instead of just relying ECT, RCT or Mullen. When compared with the experimental data Hann found that panel collapse had a linear regression R^2 value of 0.86 and found that "The McKee et. al. model agrees slightly better”. Hann acknowledged that the McKee et. al. equation considers both ECT and Flexural stiffness while his own experiment only evaluates the compressive strength of an entire panel. Hann did not ultimately build a formula for industry use but did provide set forth a new testing procedure for the evaluation of whole panels.

In 1993 Batelka and Smith continued the process of reiterating the McKee et. al. equation. Their work produced an equation capable of dealing with very short boxes unlike previous equations, with increased predictive accuracy of 68% over the original McKee equation for all box sizes, and 42% for boxes within McKee’s original dimensional limits (Equation 12). The model was verified with 81 boxes (Batelka 1993). The key addition to the Batelka equation is box height (Equation 7). In addition to the standard RSC boxes Batelka and Smith included equations for Bliss Boxes and Hexagonal boxes (these equations are not included here).

Equation 12

$$P = 1.014(P_m)^{0.746}(D_x D_y)^{0.127}(\sum (W)^{0.492})(1.593(d)^{-0.236})$$

Where

$P =$ Compression strength (Lb)

$P_m =$ Edge crush test strength (Lb/in)

$D_x =$ MD flexural stiffness (in-Lb.)

$D_y =$ CD flexural stiffness (in-Lb.)

$W =$ Width of each panel (in)

$d =$ Box depth (in)

Finite Element Analysis

Finite Element Analysis (FEA) of corrugated boxes is increasing in number through the work of Urbanik and Saliklis 2003, Biancolini and Brutti 2003, and Nordstrand 2003. FEA has demonstrated a high level of accuracy in predicting the compression strength of empty corrugated boxes (Nordstrand 2003). Currently the industry does not have a packaging specific graphical user interface which results in low market penetration for such an effective tool.

2.2 Factors Affecting the Strength of Corrugated Boxes

2.2.1 Production Variations

Manufacturer’s Joint

Kellicut and Landt (1958) provided corrections, known as “box factors”, for taped and stapled manufacturing joints. The staples joints were found to be slightly stronger however; in current markets the manufacturers’ joint is glued 90% of the time (Singh 2006). As a result, Kellicut’s box factors are not as relevant today due to improvements in manufacturing quality (Fibre box handbook 2002). Singh (2009) studied the effects of tape, glue and staples on box compression and found that there is no discernable difference in compression performance with modern techniques (Singh 2009).

Creasing

General Electric and the Forest Products laboratory conducted a broad survey of their companies corrugated boxes and found that variation in the horizontal creases had a noticeable effect on box compression strength versus the predicted failure load (McKinlay 1960). Kutt and Mithel 1969 found that crease depth of vertical corners did not have an impact on overall compression strength. (Kutt and Mithel 1969)

Flaps

In 1958, Kellicut and Landt performed a test comparing an RSC box against a tube. The tube, or sleeve, is a box with all flaps removed. This was tested for the purpose of simplifying the box component in the hopes of better understanding what the sidewalls contribute to the overall compression data. Kellicut tested the sleeves in a variety of sizes and found that a box is 30% weaker than a tube of the same dimensions. The scores and flaps of a box potentially contribute up to 30% reduction in box strength (Kellicut 1958).

McKee et. al. (1957) evaluated this phenomenon further and found that the flaps and score lines account for about 90% of box deflection. McKee et. al. also cut open a box and filmed the compression of a sidewall and flap to show that the compression of the flaps produced rotational forces on the sidewall as the flaps are compressed into the box (McKee et. al. 1957). These rotational forces compromise the vertical strength of the sidewall and are the reason why flexural rigidity is a dominant factor in the strength of boxes, especially those of larger sizes.

In 1988 Pankaj Gaur tested boxes with half of their flap length removed. He referred to this box as a "Half Flap" box (not to be confused with the half-slotted container). By removing half of the RSC's flap length a substantial gap remained in the center of the box. Gaur tested these boxes in diagonal oriented compression where the box would be compressed from corner to corner. The results of the study found that the flap length had a substantial impact on the diagonal compression performance (Gaur 1988). Due to the unorthodox compression methodology the results of this study cannot be compared to any similar boxes.

Sealing Method

Hot melt adhesive and tape are the primary methods of sealing corrugated box flaps. Hot melt adhesive holds the major and minor flaps securely to each other. Taped boxes allow the minor flaps to rotate inside the box (Frank 2013). Free rotation decrease box deflection and increases compression strength (Maltenfort 1989).

Squareness of Box

Squareness or the degree to which all corners of the perimeter of box are 90 degrees does not have an adverse effect in normal ranges. Kutt found that corners within the range of 20 degrees to 120 degrees do not have a considerable impact on compression strength. Kutt also notes that beyond these ranges the “corner” begins to act as a panel again. (Kutt and Mithel 1969)

Filled Box

In addition to researching the method of box failure, Kellicut 1963 explored the effect of box contents on its overall compression strength. This test was conducted by building a sleeve of plywood that would fit snug inside the box while being short enough (sufficient head space) so as to not interfere directly with top-load compression. In addition to plywood, Kellicut also tested a box filled with lose corn kernels. The test found that the loose filled corn increased compression strength by 4.5%. It was also found that the plywood box support increased stacking strength by 9% or 130lbs in the case of the A-flute boxes being tested (Kellicut 1963).

In his 1957 paper, McKee et. al. conducted a smaller additional study where he inserted a shorter corrugated tube inside an RSC to simulate “product. In this way, he was able to evaluate the effects of “headspace”, the vertical gap between a product and its protective box. The testing found that box deflection, and headspace, are of critical importance. A box with too little headspace will damage the product before all of the available compression strength of the box is utilized. Conversely, excessive headspace eliminates the opportunity for the box and its contents to supplement each other’s strength, thus producing a compression resistance that would be unachievable by either element on its own. (McKee et. al. 1957)

Production Samples vs CAD or Handmade boxes

Kellicut and Landt (1958) found that hand made boxes are stronger than production samples. Previous findings indicate that this variation is due to production processes that might compress flutes, skew manufacturers joints or produce less accurate creases.

2.2.2 Supply Chain Variations

Storage Time

In the 1960’s, a study by Skidmore looked at the effect of long term container storage and the affect it would have on strength of boxes. The boxes were stored flat for 24 years, no attempt was made to control large swings in temp and humidity. The testing showed that there was little to no difference in the strength and tensile results of the corrugated paperboard after long-term storage (Skidmore 1962).

Previous Compression

In 1992 Marcondes showed that loading to 50% or more of the box’s compression strength will not significantly impact the compression strength of subsequent tests. However, pre-compression does inflict a permanent deflection in the box that result in high strain measures in the final compression test. In other words, the box does not regain lost height from deflection but does retain its ultimate compression strength. (Marcondes 1992)

Handling

Jorge Marcondes tested the compression strength of boxes after they had been subjected to shocks. To do this, he dropped C-Flute boxes (400mm x 270mm x 170mm) from a height of 0.5 meters, and tested the compression strength after 2, 4, 6, 8 and 10 drops. (Marcondes 1992). Marcondes concluded that impacts have a negative effect on final box compression strength. This finding is significant for packages being shipped in parcel delivery environments where the occurrence of drops is much higher than that experienced by boxes in a unit load (Soroka 2002).

Vibration

Marcondes also evaluated the effects of vibration on the strength of corrugated boxes. These include but are not limited to Pennington (1996), Godshall (1986), Urbanick (1990), and Prather (1997). Each has come to interesting yet varying conclusions about the effect of vibration. It is worth noting that the impact of vibration on box performance is dependent on frequency, GRMs, and vibration time, in addition to other factors. In 1968 Goodshall found that a history of vibration would reduce box compression strength by 1.25% (Goodshall 1968).

Moisture Content

The moisture content of paper directly affects the compression strength and other physical properties of a box. Equation 13 was developed by Kellicut and Land in 1959 to adjust box compression strength based on moisture content. Kellicut (1959) later stated that “a specific increase in moisture content reduced the crush strength of the treated board by the same percentage” reflected in Equation 12 (Kellicut 1959).

Kellicut’s results were confirmed by McKee et. al. and Whitsitt in 1972. McKee et. al. also noted that the percent moisture content has a greater effect on long term warehouse stacking strength, than it does on a relatively short compression strength test. Several variations of this study have been conducted by Scott, R. A. in 1959, the Fordriner Kraft Institute in 1968 and Greenway, G. W. in 1970, and Kawanishi in 1989 who established a rule of thumb; 1% increase in moisture content equals 10% reduction in compression strength (Kawanishi 1988).

Equation 13

$$Y = b(10)^{mx}$$

Where Y = compression strength of box in Lbs

b = compression strength at 0% moisture content

m = -3.01 slope constant

x = moisture content expressed as a decimal

The primary disadvantage of Equation 13 is that it requires the compression strength of a box at 0% moisture content. Such a test would require a test set up capable to drying the paper to 0% and being able to subsequently conduct compression testing inside that environment. Kellicut solved the issue with Equation 14, which uses the compression strength of a box, tested at a known moisture content, to predict the strength at a different moisture content.

Equation 14

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

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

2.2.2.1 Relative Humidity

The equilibrium moisture content of paperboard is directly affected by the ambient relative humidity, and to a lesser degree, ambient temperature (Maltenfort 1988). Zhao 1993 found that the moisture content of the box changes rapidly based on the relative humidity, with changes in MC% occurring almost instantly as RH% changes. Due to the rapid change in moisture content ASTM 4334 (Practice For Conditioning Paper and Paper Products for Testing) recommends testing in a controlled environment. When testing in a controlled environment is not possible ASTM 4334 recommends wrapping the specimen in plastic to maintain moisture content during testing.

The relationship between equilibrium moisture content and the relative humidity is called the moisture sorption isotherm. For paper, the moisture sorption isotherm is not linear, nor is it the same for adsorption and desorption. In 2007, Singh et. al. found that in a temperature control lab with relative humidity of less than 50%, any subsequent changes of 15% relative humidity have a minimal effect on box compression strength (Singh et. al. 2007).

Paper material should also be considered when testing boxes. Moisture sorption rate for recycled paper is lower than virgin fiber and the final equilibrium MC% is lower than virgin fiber (Zhao 1993). The lower moisture sorption rate provided a distinct advantage for recycled boxes compared to virgin when exposed to cyclic relative humidity. Zhao findings also limit the application of Kellicut and Land 1959 (Equation 14), which is applicable only to uncoated virgin Kraft paper.

2.3 Failure Modes

McKee and Gander used high-speed cameras to film origin and propagation of box failure. The team found “that failure initiates at a vertical edge and from there progresses into the panels….these results imply that the vertical edges of the box are the most highly stressed regions.” (McKee et. al. 1957). McKee also describes propagation of the buckling in a semicircle from one corner to the next in what he calls the “characteristic crescent shape” failure, sometimes informally referred to as the “smiley face”. This failure mode is indicative of highly complex shear stress across the sidewall but does not always correlate with complete box failure (McKee et. al. 1957).

3 Pallets

Every day there are approximately 2 billion pallets in circulation (White 2005). Half a billion new pallets are produced annually to replace those lost or destroyed (Araman 1999). Wooden pallets alone comprising 95% of the pallet market however, plastic, metal, paper and composite are also available (Clarke 2004, White 2005).

3.1 History

Before pallets, the primary form for transport and storage of goods was the traditional wooden barrel (LeBlanc 2003). Early lift truck technology began to emerge in the late 1800s as the successor to hoists and platform trucks (LeBlanc 2003). Pallets were being used as early as 1930's but the global logistical demands of WWII proved the pallets efficiently in loading, unloading and tracking of supplies. At the time the military had standardized four pallet sizes, none of which are still in existence today (LeBlanc 2003). The first pallet patent seems to be developed by the Lyons Iron Works Company of New York (US Patent 2,178,646 filed 1937)(**Figure 15**) by George Raymond and William House. The patent acknowledges that pallet field is well established yet lacking in ease of use. Raymond's patent brought together design elements from various pallets along with the ability to be accessible with a hand truck that was being designed and patented simultaneously. The result is what is now referred to as a 2-way stringer pallet (see section 4.1.1. stringer pallets). One drawback of Raymond's 2-way pallet design is the limited forklift access; front and back. Raymond's patent specifically shows a pallet jack, five years before Herbert Framhein filed his designs for pallet jacks in 1942 and 1943 (US Patent 2,399,596 and 2,417,395).

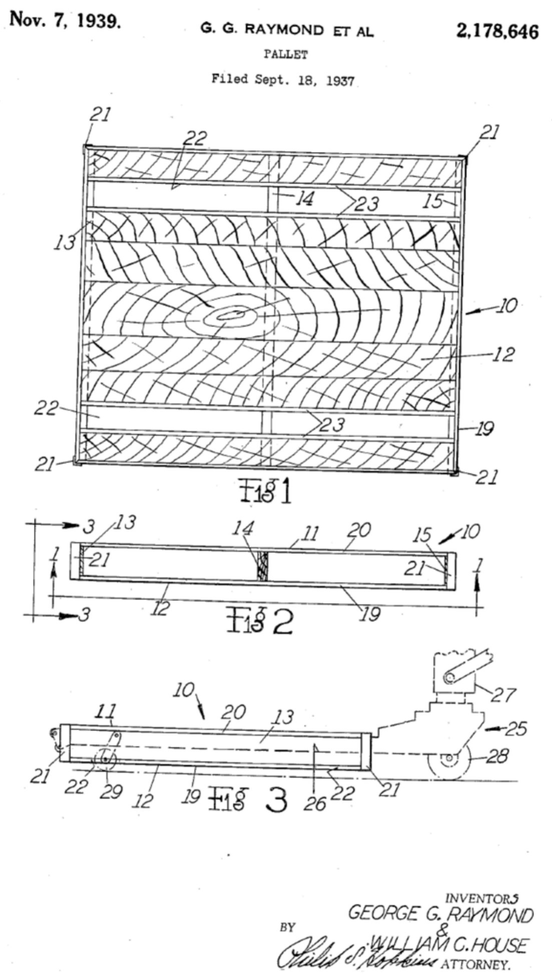

Figure 15 Two-way pallet, patent 2,178,646 filed in 1937 by George Raymond

While working at the MA Naval Depot in 1943, Norman Cahner filed a patent for a pallet that allowed a forklift to access a pallet from all four sides (US Patent 2,369,944) (**Figure 17**)(LeBlanc 2003). Cahner's pallet eventually became todays standard 48 in. x 40 in. pallet (Mil-P-15011J size A) and was a significant advantage in the war effort from a logistical standpoint (Mil-P-15011J 1981). Cahner went on to found Modern Materials Handling Magazine, which is still in print today (LeBlanc 2003).

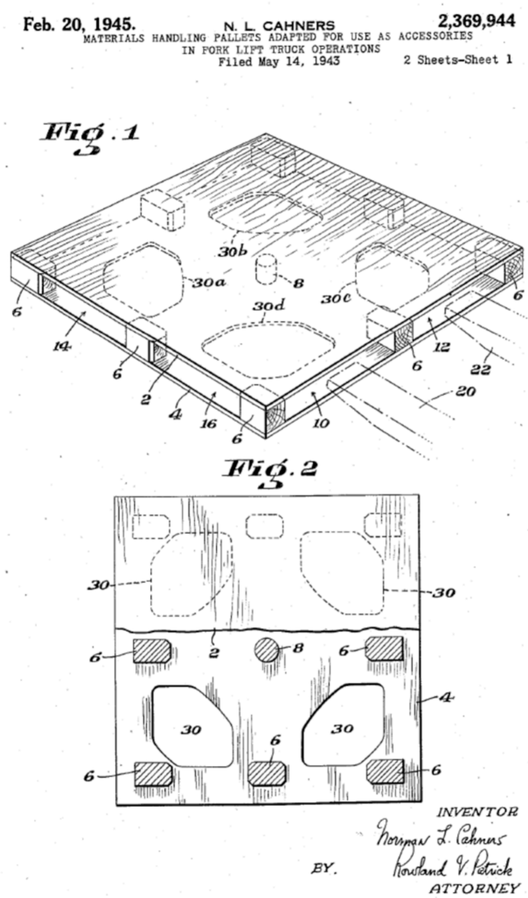

Figure 16 US Patent 2,369,944 for the first 4-way accessible pallet

After WWII the pallet industry saw a surge in use amongst the rail and shipping companies looking to reduce labor. The introduction of the pallet created conflict with longshoremen unions who feared the loss of jobs that would result from the significant drop in product handling (LeBlanc 2003). In the 1950's General Foods Company realized the logistical benefits of standardization. The company required its customers to use 48 in. x 40 in. pallets which became the de facto industry standard (LeBlanc 2003). General Foods specification was later adopted by the Grocery Manufactures of America (GMA) standard now simply known as the GMA-style pallet.

Clarke 2004 found that 30% of pallets produced are of the GMA type and a survey by Park in 2012 found that 72.3% of pallets being for recycling are built to GMA specifications (Clarke 2004, Park 2012). Pallet recyclers, and pallet poolers also benefited for a common footprint, which allowed them to leverage their scale (LeBlanc 2003).

3.2 Pallet Classes and Common Dimensions

Pallets are divided into two main classes; stringer pallets and block pallets (figure 17). A 2001 survey by Bejune found that stringer and block pallets make up 80% and 20% of the industry respectively, thought there is indication that this trend is shifting (Bejune 2001).

Pallets come in a variety of standard sizes to suit different needs country standards. **Table 2** lists the standard pallet by region as recognized by the International Organization for Standards.

Table 2 ISO 6780 (2003) recognized standard pallets

Continent	SI (mm.)	US Customary (in.)
Europe, Asia, India, Central and South America	1200 x 1000	47.24 x 39.37
Europe, Asia, India	1200 x 800	47.24 x 31.50
North America	1219 x 1016	48.00 x 40.00
Australia	1140 x 1140	44.88 x 44.88
Asia	1100 x 1100	43.30 x 43.30
North America, Europe, Asia	1067 x 1067	42.00 x 42.00

3.2.1 Stringer Pallet

Stinger pallets are the most widely used type of pallet and benefit from low cost and ease of manufacturing (LeBlanc 2003). Stringer pallets use wood members, called stringers, to define the length of the pallet and provide spacing between the top and bottom deck boards (Clarke 2004) (**Figure 17**). A typical stringer is comprised of a nominal 2 in. wide x 4 in. tall (1.5 in. x 3.5 in.) x 48 in. length piece of lumber. As a result of the nominal 2 in. x 4 in. stringer the gap between the deck boards is 3.5 in. Other stringer sizes are available and may be used to accommodate higher loads or larger products. The vast majority of pallets utilize 3 stringers, one inside stringer that is centered along the pallet width and two outside stringers. The outside stringers are traditionally flush with the outside edge of the deckboards however if they are recessed the pallet is known as a winged pallet due to the overhanging deckboards.

Stringer pallets can be manufactured in 2-way and partial 4-way varieties. A 2-way stringer pallet is only accessible with a pallet jack and forklift from the 40 in. sides parallel to the stringers. Partial 4-way pallets have notches cut into the underside of the stringer to allow a forklift access to the 48in side. The pallet is called a partial 4-way because the stringer notches are not tall enough to accommodate the larger blades of pallet jack in the notches.

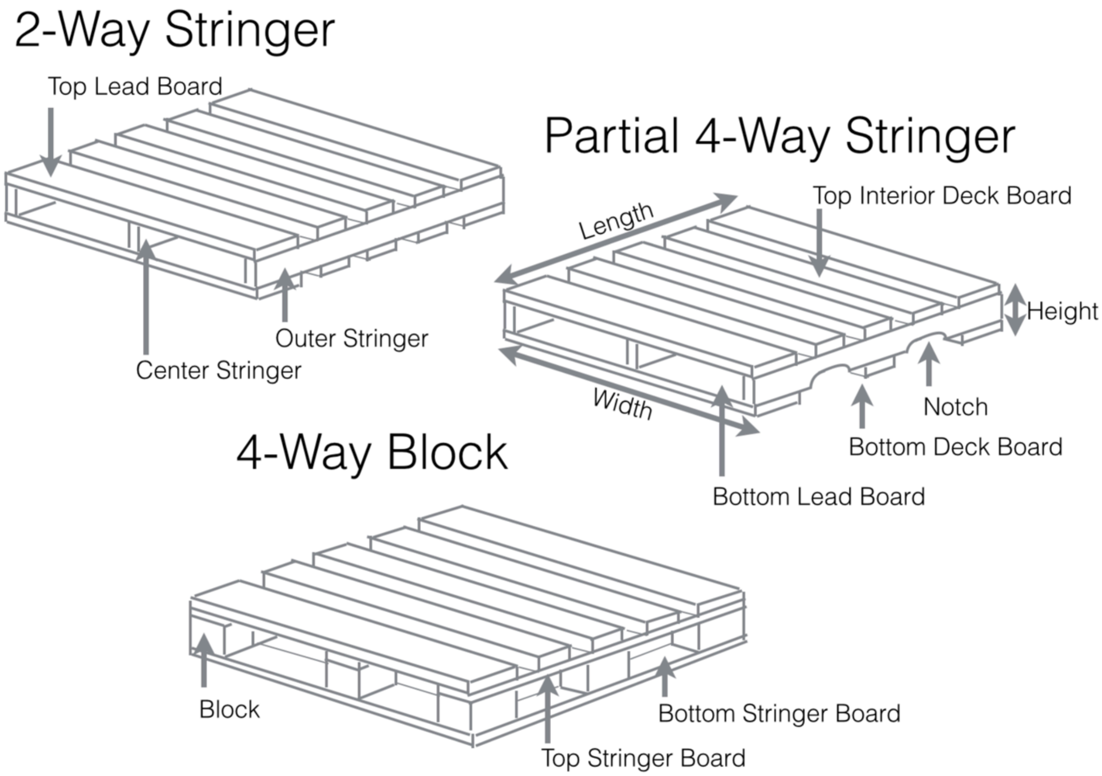

Figure 17 shows the two types of stringer pallet and the block pallet.

3.2.2 Block Pallet

Block pallets are differentiated from stringer pallets by their use of nine wood blocks (**Figure 17**). The blocks are tied together with top and bottom stringer boards that run the length and width of the pallet and differ significantly from those found in stringer style pallets. The top deckboards are then fastened to the top stringer boards. Block pallets allow for 4-way entry for both hand jacks and forklifts.

Generally speaking the block style pallet is considered stronger and more durable than a stringer pallet (Brindley 2008, Twede 2005). As a result the block design has become the favored pallet of pooling companies who rent pallets and thus require a pallet that need to accommodate multiple uses and long durations in the field.

3.3 Pallet Testing

ASTM 1185 and ISO 8611 cover a range of pallet related tests including but not limited to: drops, incline impact and compression testing in a variety of storage conditions. Storage conditions determine which components of the pallet is most stressed and most susceptible to failure. The following will highlight each component of a stringer pallet and address the relevant concerns and testing protocol for each.

Stringer Testing

Stringers provide support along the length of the pallet when pallets are placed in drive-in rack system or lifted by the notches. These scenarios can be simulated with ISO 8611-1 and 8611-2, respectively. Gerhardt (1984) showed that the strength of a stringer is dependent on notch depth, with larger notches causing significant decreases in strength. Gerhardt demonstrated that using a fillet instead of a square cut increased the strength of the stringer.

Top Deckboards Testing

In GMA pallets the lead deck boards are nominally 6 in. in width, while the interior deck boards are nominally 4in in width and their length defines the pallet width. The top deckboards provide a large surface area for products to sit on top of a pallet. (Heebink 1956, Urbanick 1985). The maximum weight a pallet can support in any given set of condition is referred to as the “load carrying capacity”, which is nearly always determined by the deckboards (Heebink 1956). The top deckboard determines pallet strength in floor stacking and fork tine support while both top and bottom deckboards provide support when a pallet is being stored in a drive in racking system (**Figure 18**)

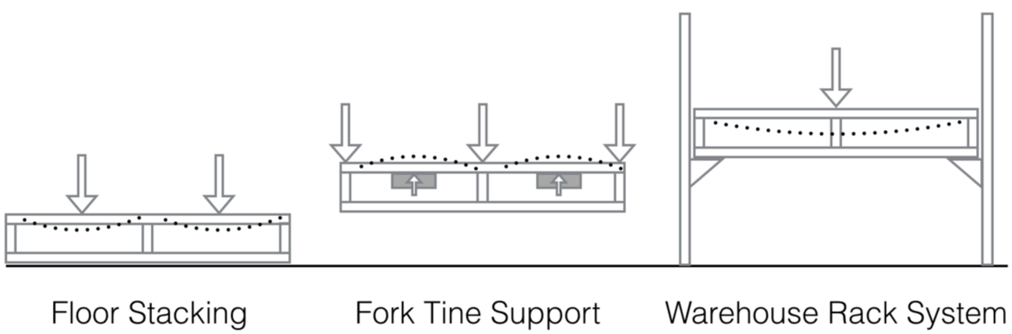

Figure 18 Front view of force distribution on deckboards in here different support conditions.

The most common deckboard sizes are 3.5 in. wide by 0.75 in. thick and 5.5 in. wide by 0.75 in. thick, but other sizes are available to accommodate higher loads or cost criteria. The following formula developed by Heebrink (1956) and is a basic adaptation of beam theory to pallet deckboards (Equation 15). Deckboard strength is dependent on the span. Pallets typically have three stringers but the addition of a fourth stringer reduces deckboard span and increases deckboard strength. Loferski 1988 found that deckboards under deflection rotate around the inside edge of the stringers. Therefore, the span in Heebrink 1956 formula (Equation 15) for the maximum load carrying capacity of pallet deckboards is defined as the free span between stringers from inside-to-inside.

Equation 15

$$W = 2\frac{bd^2}{s}f$$

Where:

$W =$ load carrying capacity of deckboards (lbs)

$b =$ width of deckboard (in)

$d =$ thickness of deckboard (in)

$s =$ span between stringers (in)

$f =$ basic stress of clear lumbar (psi)

Bottom Deckboards

Bottom deckboard strength can be measured with ISO 8611-5 and are subject to the same equation used for top deck strength (Equation 15). The bottom deckboards primarily interact with the floor or with the top of other products when unit loads are double stacked. Double stacking will subject the bottom deckboards to the full weight of the unit load above and the uneven surface of the unit load bellow. Bottom decks have less total surface area so the compression forces in double stacking are greater.

Fasteners

The strength and stiffness of any given pallet component is dependent on the method by which it is secured. Urbanik (1985) expanded on Heebrink's 1956 work by studying top and bottom deckboard defection in a drive in rack system (**Figure 18**). Urbanick provided calculations for strength and deflection while accounting for the fixture method and found that the joints rotational modulus affects the strength and stiffness of the pallet. Both, pinned and fixed joints were evaluated in the study. The pinned joint allows for rotational movement at the point of contact with the stringer, where as the fixed joint holds the board ends ridged and forces bending to occur within the beam. Yoo 2011 studied the effects of pallet joints and deckboard stiffness as part of a larger study and found that free joints deflected more than fixed joints and as a result have a significant effect on the forces that are transferred to the packages above.

American National Standard MH1 for Pallets, Slip Sheets, and Other Bases for Unit Loads (2005) specifies the minimum quality of fasteners that can be used for mutli-use and single-use pallets. The quality of a fastener (nail or staple) is determined by its fastener withdrawal index (FWI) and its fastener shear index (FSI). FWI is a measure of force required to pull a nail from the pallet while FSI is a measure of nail bending when impacted with a set weight. Measuring the FWI and FSI of a fastener is outlined in the Protocol for Measuring the Quality of Pallet Nails and Staples by Stern and White 1997.

3.4 Factors Affecting Deckboard Strength and Stiffness

Physical Factors

Pallets conform to the basic engineering principals of beam theory with added complexity caused by variability in wood and human assembly. Properties to consider are: width and height of the board along with species, grain direction, and knots (Heebrink 1956). Hardwoods often have better strength and durability in addition to increased purchase/FWI on nails compared to softwoods (Heebrink 1956). Softwoods benefit from lighter weight, workability and affordability (Heebrink 1956). Pallet components experience wear and breakage in the transportation environment, which adversely affects pallet performance.

Environmental Factors

Wood is susceptible to environmental conditions. Relative humidity and temperature will directly affect the moisture content of wood. As moisture content increases strength and decreases stiffness until the wood reaches its fiber saturation point of roughly 30% (Gerhards 1982). Factors such as age, damage, and duration of load will change the strength and stiffness properties of wooden deckboards and should be taken into account when designing pallets (Heebrink 1956). Other factors affecting wood strength are mold damage, geography, heartwood, compression and tension wood, and location of cut within the log (Wood Handbook 2010).

3.5 Pallet Design

Pallet Design System (PDS®) (NWPCA, 1984) and Best Load ™ (White and Company, 2011) are two programs capable of designing and specifying wooden pallets. Both systems are capable aiding the design process by predicting the strength of a design and optimizing the final product in the interest of cost (Loferski 1988).

4 Unit Load

Primary packaging consists of the material in direct contact with the product. Secondary packaging is any corrugated box or system that contains, protects or bundles the primary package. Tertiary packaging is the pallet, slip-sheet, stretch wrap and other load containment that are used in conjunction with the primary and secondary packaging to form a cohesive unit load. A unit load is a single entity that can be managed, inventoried, stored, shipped, handled as a single unit. Prior to the innovation of the wooden pallet stevedores, or longshoremen would handle products manually (LeBlanc 2003). The work was dangerous and product were easily damaged or stolen (Kestenbaum 2013). Palletization made it possible to track and ship goods in bulk units that are less susceptible to loss or damage (Twede 2005).

For much of history the box, the warehouse, the pallet and other packaging, have been developed independently from one another. This process of independent design and developments is known as component based design (White 2005). Component based design cannot achieve optimal performance of all components simultaneously and therefore, performance, price, and sustainability are sacrificed.

4.1 Pallet – Corrugated Box Interactions

Boxes on a pallet have lower compression strength than boxes tested on the flat surface (Kellicut 1963).

4.1.1 Pallet Gaps

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. GMA pallets have gaps between deckboards of 1 and 3 inches (Ievans 1975).

Ievans (1975) studied 24 in. x 15.5 in. x 12 in. C-flute boxes with pallet gaps under the width sidewall and the vertical corners of the box fully supported. Ievans reported that there was no significant impact of case compression strength when the gap 3 in. or less. When the gap was increased to 7 in. the box lost 15% of its compression strength. In 1992 Monoghan and Marcondes tested C-flute cases with dimensions of 400 mm. x 270 mm. x 170 mm. over pallet gaps of 0, 40, 80, 120, and 160 mm. It was found pallet gaps reduced box compression strength exponentially and not linearly (Monoghan 1992). The team produced

Equation 16, which is specific to the box tested (R^2=0.992).

Equation 16

$$Y = 1226^{-0.006X+0.992}$$

Where

Y = compression strength in N

X = gap in mm

DiSalvo's (1999) study used a combination of overhang treatments, deckboard gap treatments and interlock stacking to determine if the loss in compression strength was compounding. 10 in. x 6 in. x 6 in B-Flute and tested at pallet gaps of 0%, 5%, 15%, and 25% of the width of the sidewall. It was found that the pallet gaps resulted in strength reductions of 7.7% to 12.9%. It is noteworthy that DiSalvo defined pallet gaps as a percentage of box area instead of simply the distance in mm. or in. as had been done previously. When combining overhang treatments and deckboard gap treatments the study found the two factors were not compounding. Instead the total compression strength loss was 11% less than expected. A comparison of findings from all three previous studies is outline below in **Table 3**. The results indicate that there significant variation between study results.

Testing conditions were noted to have varied from 35% to 50% RH and 20 to 26 °C, and the results of the compression test were then amended to compensate for relative humidity in the testing room. Relative humidity correction was necessary to normalize all results to standard atmospheric conditions of 50% RH (DiSalvo 1999).

Table 3 Comparison of three presious pallet gap studies at each pallet gap tested.

Author		Ievans	Monaghan (Predicted)	DiSalvo
Year		-1975	-1992	-1999
Box Size		24 in. x 15.5 in. x 12 in.	15.75 in. x 10.6 in. x 6.7 in.	10 in. x 6 in. x6 in.
Flute		C-flute	C-flute	B-flute
Gap (% of sidewall width)	**5%**	-	-2.40%	-7.70%
	15%	-	-6.80%	-10.40%
	20%	0.00%	-8.70%	-
	25%	-	-10.40%	-12.90%
	33%	-8.00%	-13.00%	-
	47%	-15.00%	-16.70%	-

4.1.2 Box Overhang

In 1975 Ievans studied the effects of over hang on single and double-wall boxes and found that overhang contributed to significant reductions in box strength (Ievans1975). Overhang is the result of one or more vertical panels of a box not being supported by a pallet or box. Ievans evaluated a variety of overhang distances and orientations and predictably found that as the box lost sidewall support the stacking strength decreased. The most severe treatment had two adjacent sidewalls overhung by 1.5 inches each direction resulting in 49% loss of strength. The least sever treatment consisted of a 0.5 in overhang of the width panel, resulting in 14% reduction in box strength.

In 1992, Monaghan and Marcondes repeated this study and corroborated the earlier findings. The team made an attempt to produce a regression model from the study but were unable to do so because of a 38% variation in the data (Monaghan 1992). In 1999, DiSalvo again tested overhang on 10in x 6in x 6in B-flute boxes and found strength reductions between 30.5% and 42.1 (DiSalvo 1999).

Single boxes are only a part of the larger unit load picture. If a pallet pattern has overhang it is common for the entire face to overhang the pallet. Ievans studied the effect of overhang in a unit load. When the column-stacked pattern was subjected to a 1 in overhang the compression strength of the unit load was reduced by 32%. When the same study was repeated with an interlocked pallet pattern the compression strength of the unit load was reduced by only 8%.

4.2 Pallet Pattern

The pallet pattern is defined by the number and specific arrangement of boxes in a unit load. Any given layer of boxes can be arranged in a variety of ways to optimize the number of boxes per layer. A packaging engineer generally strives to maximize efficiency by placing the highest number of boxes possible on a pallet. Software such as CAPE, TOPs and Best Load aid this endeavor to maximize efficiency.

The orientation of a box layer with regards to the layer above and below are defined in two ways. If the boxes are arranged so that any given box sits directly on the box below with all vertical panels aligned it is said to be column- stacked. If the boxes do not align vertically, or there is a meshing of the layers, the pattern is said to be interlocked.

4.2.1 Interlock and Column stack

In Kellicut's 1963 study, a full pallet of empty A-flute boxes (8 per layer and 3 high) was tested on a flat platen for compression strength in both a column stacked pattern and an interlocked pattern. The interlocked patterned lost 39-45% of its vertical compression strength compared to the column-stacked pattern (Kellicutt 1963).

4.2.2 Column versus Misalignment

Both Kellicut (1963) and Ievans (1975) conducted testing of boxes stacked vertically three high in an attempt to simulate pallet stacking. This methodology was chosen to eliminate the variability of the practically unlimited number of pallet pattern variations and to determine if the method could help simulate full unit loads when larger compression testing equipment was unavailable.

The perfectly aligned column stack was compared to a "misaligned" stack that was used to simulate an interlocked pallet pattern. Offsetting the middle box by a half inch in both the X and Y direction simulated the interlocking effect (Figure 19). Compared to the stacking strength of a single box, both Kellicut and Ievans found that three high column stacking decreased strength around 20-30%. When comparing the three high column stacks to the three high misaligned stack both parties found an additional 27-29% reduction in stacking strength (Kellicut 1963, Ievans 1975). The three high misaligned test represents a "double overhang" situation and does not accurately replicate the forces a box will experience in a unit load. As a result both parties made no attempt to correlate this data to the results obtained at the full unit load scale.

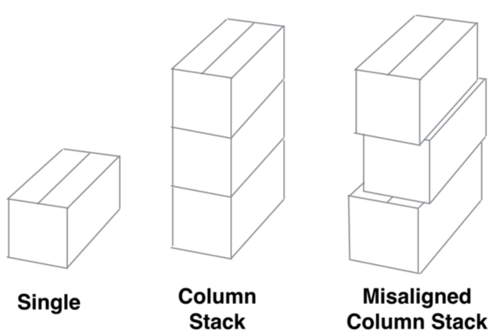

Figure 19 Three high stacking of boxes as used by Kellicut and Ievans to simulate column and interlocked pallet patterns

Park (2010) found that the reduction in compression strength due to misaligned stacking can be predicted using Equation 17. From this study Park found "every 1% offset in length or width direction, an empty box losses about 2.5% of its compression strength" (Park 2010).

Equation 17

$$\frac{OCS}{CCS} = 1 - 2.55\left(\frac{x}{L} + \frac{y}{W}\right)$$

$Where:$

$OCS =$ offset compression strength

$CCS =$ control compression strength

$x =$ length panel offset

$y =$ width panel offset

$L =$ length of box

$W =$ width of box

4.3 Load Containment

Load containment is any method used to secure the unit load into one cohesive structure. Stretch wrap, shrink-wrap and banding are the most commonly used load containment methods. Stretch wrap is a thin plastic film, usually made from linear low density polyethylene (LLDPE), that is pre-stretched and wrapped horizontally around a unit load. As the plastic recovers from the pre-stretch it produces a tensile force that acts as a horizontal containment force on the unit load (Cernokus 2012). Stretch wrap can be measures using ASTM D 5459-95. Stretch wrap out performs other methods of load containment in preventing horizontal shifting in the unit load during vibration and incline impact, however the containment force did not have statistically significant effect on the horizontal shift (Bisha 2012).

4.4 Load Bridging

Load bridging occurs when a product sitting on a pallet deflects less than the pallet under load (Fagan 1982). The discrepancy in deflection is due to the product having a greater stiffness than the pallet itself. Product size, type, stiffness and pallet pattern have an effect on the degree of load bridging (Collie 1984). White (1999) determined that load containment has a significant effect on load bridging with vertical strapping found to be the most effective at preventing the effect. Yoo (2008, 2011) found that load bridging caused uneven distribution of forces between the pallet and the package, which negatively impact the performance and safety of pallets and packages.

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Chapter 1: Predicting the Effect of Gaps Between Deckboards on the Compression Strength of Corrugated Boxes

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1 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.

2 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.

(1)

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

Where :

P = compressions strength (kg)

P_m = edgewise compression strength (kg/mm)

h= combined board caliper (mm)

Z= box perimeter (mm)

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 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.

3 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.

4 MATERIALS

4.1 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 20). The boxes were manufactured by Corrugated Container Corporation in Roanoke, Virginia.

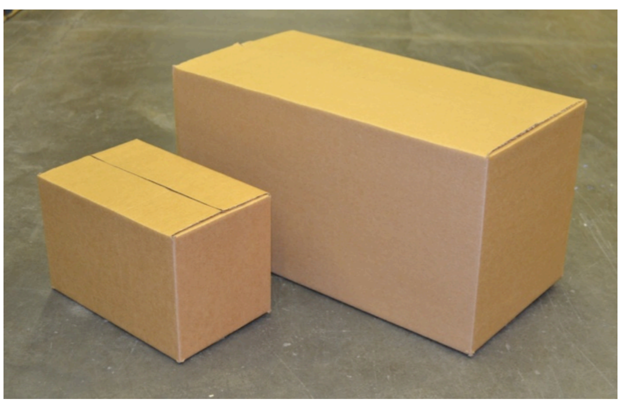

Figure 20 Side-by-side comparison of assembled RSC sample boxes 254 mm x 152 mm x 152 mm (front left) and 508 mm x 305 mm x 305 mm (back right)

4.2 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.

5 Methods

5.1 Compression Testing

The boxes were placed on the wooden boards so that the box sidewall being tested was centered over the gap (Figure 21). 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 [19].

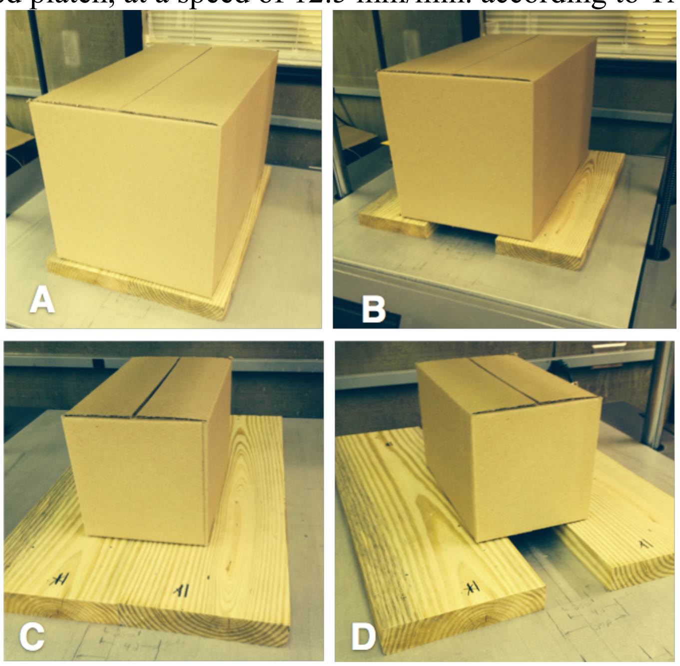

Figure 21 Experimental setup with boxes centered on deckboards inside the Lansmont compression tester. A) "Large" box on 0 mm gap. B) "Large" box on 165 mm gap under width panel. C) "Small" box on 0 mm gap. D) "Small" box on 83 mm gap under width panel.

5.2 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 °C and 50% relative humidity. [5,14]

$$\text{Moisture Content \%} = \frac{(W_1 - W_2)}{W_2}(100) \qquad (2)$$

Where $W_1 =$ Sample weight before drying

$W_2 =$ Sample weight after drying

(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

5.3 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].

6 Design of Experiment

6.1 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.

6.2 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 21A).

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 22**B) 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 4**.

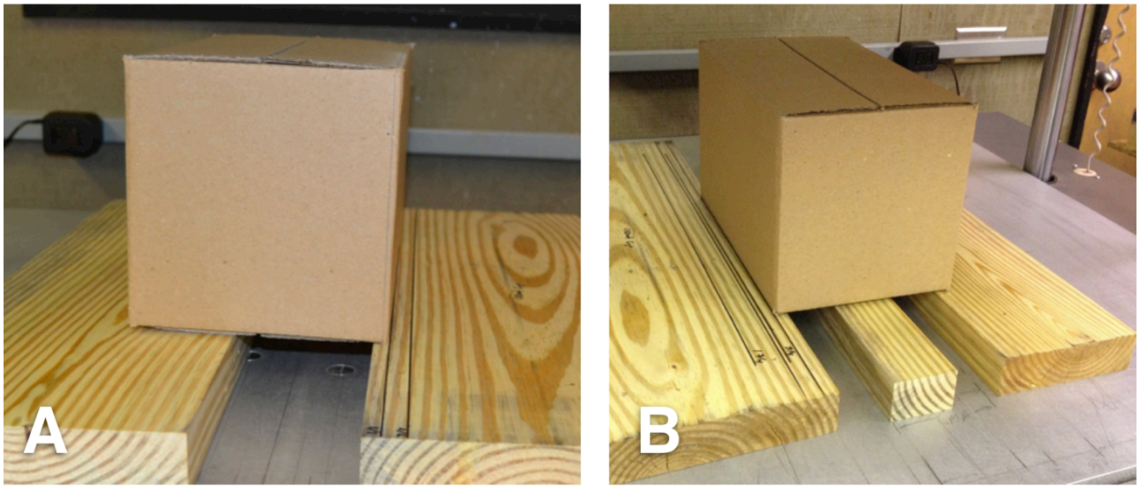

Figure 22 A) The 254 mm x 152 mm x 152 mm box supported by deckboards with 83 mm and positioned off-center by 13 mm. **B)** Test setup for double-gaps between deckboards using three simulated deckboard segments with two 42.5 mm gaps, which total 83 mm.

Table 4 Summary table of support provided by deckboards when box is positioned off-center from the gap and spanning multiple gaps.

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

7 RESULTS AND DISCUSSION

7.1 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. The small sample size and lack of moisture hysteresis control in DiSalo’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.

The data indicates that the reduction in box compression strength caused by the gap between deckboards is independent of panel being tested. When the same size gap was placed under the length and 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 23).

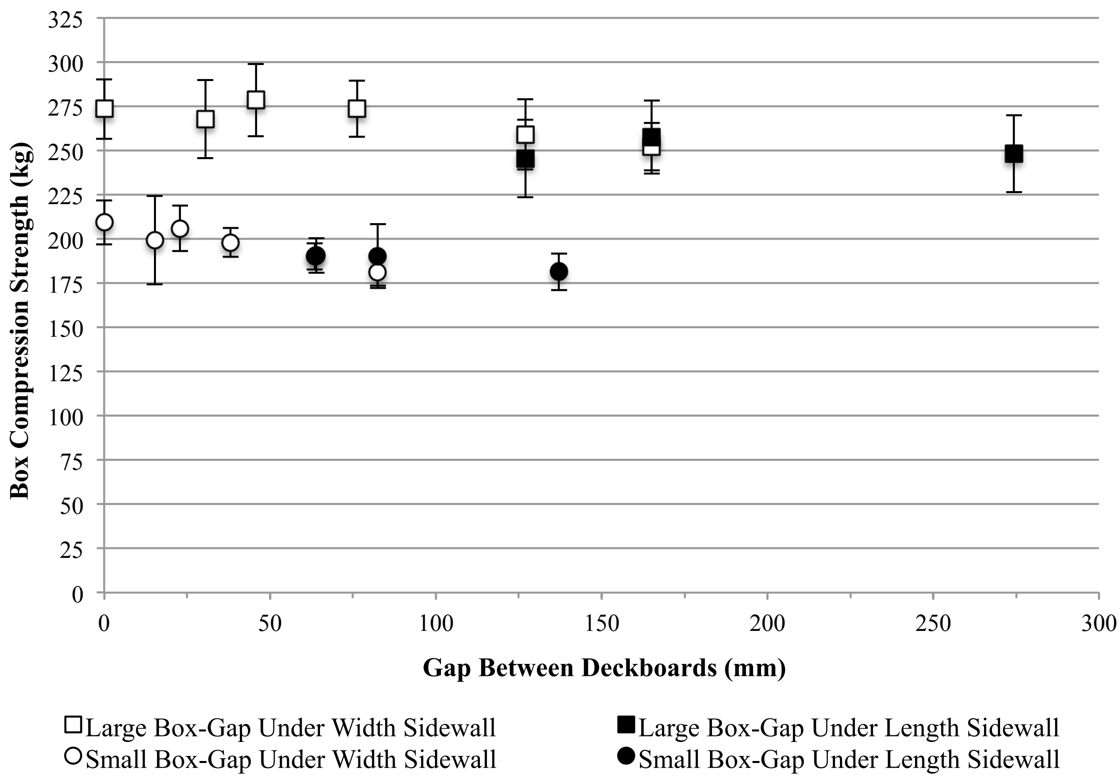

Figure 23 The effect of gaps on the compression strength of 508 mm x 305 mm x 305 mm "Large" box and 254 mm x 152 mm x 152 mm "Small" boxes.

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 24).

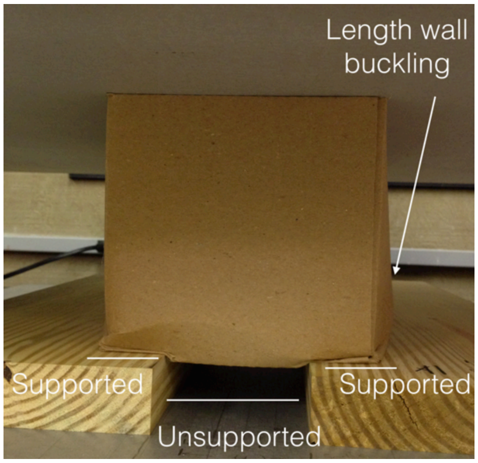

Figure 24 Picture of “Small” box failure showing failure due to bucking of the right sidewall.

7.2 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 5). Additionally, testing showed that the 83 mm gap could be subdivided into a double-gap without significantly affecting the box compression strength.

Table 5 Summary table of boxes compression test results at different locations and number of gaps. Note: values in parentheses are Coefficient of Variation values.

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

* significantly different from control by Student’s-T Test at α=0.05.

7.3 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 25). 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.

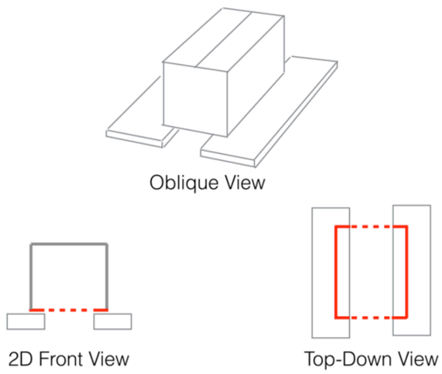

Figure 25 Representation of 254 mm x 152 mm x 152 mm box showing oblique view (top). Front view with dotted line representing the loss in sidewall support caused by the gap between deckboards (left), and top-down view with dotted line representing the loss in perimeter support caused by the gap.

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.

Equation 4 shows the proposed modification to the McKee equation. The gap between deckboards (G) is doubled to account for the loss of support at two opposite panels before it is subtracted from the box perimeter (Z).

$$P = 5.87 P_m \times \sqrt{h \times (Z - 2G)} \tag{4}$$

Where :

$P =$ compressions strength (kg)

$P_m =$ edgewise compression strength (kg/mm)

h= combined board caliper (mm)

Z= box perimeter (mm)

G= gap between deckboards (mm)

To analyze the usefulness of Equation (4), the tested results were compared to the predicted compression strength. The listed edgewise compression strength (ECT) on the box manufacturers certificate (BMC) is a conservative estimate of ECT and will 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 found that the ECT of the corrugated board is 0.67 kg/mm (equivalent to 37.5 lb/in). When box strength was calculated using the tested ECT value equation (4) under estimated the actual compression strength by an average of 13.2 kg with an average error of 8.2% (Grey line Figure 7). While under estimating box strength is far safer than an 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 the box compression test (BCT) value as a function of the size of the pallet gaps (5). The predictions under predicted box strength by 6.8kg with and average error of 5.8% and 95% of the error with 6.5% (Black line Figure 26). By comparison, 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 adjustment not taken place the average error would have been 8.6%. Therefore, adjusting for moisture content represents a 32% reduction in error.

$$GBCT = BCT \times \sqrt{\frac{Z - 2G}{Z}} \tag{5}$$

where :

$GBCT =$ gapped box compression strength (kg)

$BCT =$ box compression strength (kg)

$Z =$ box perimeter (mm)

$G =$ gap between deckboards (mm)

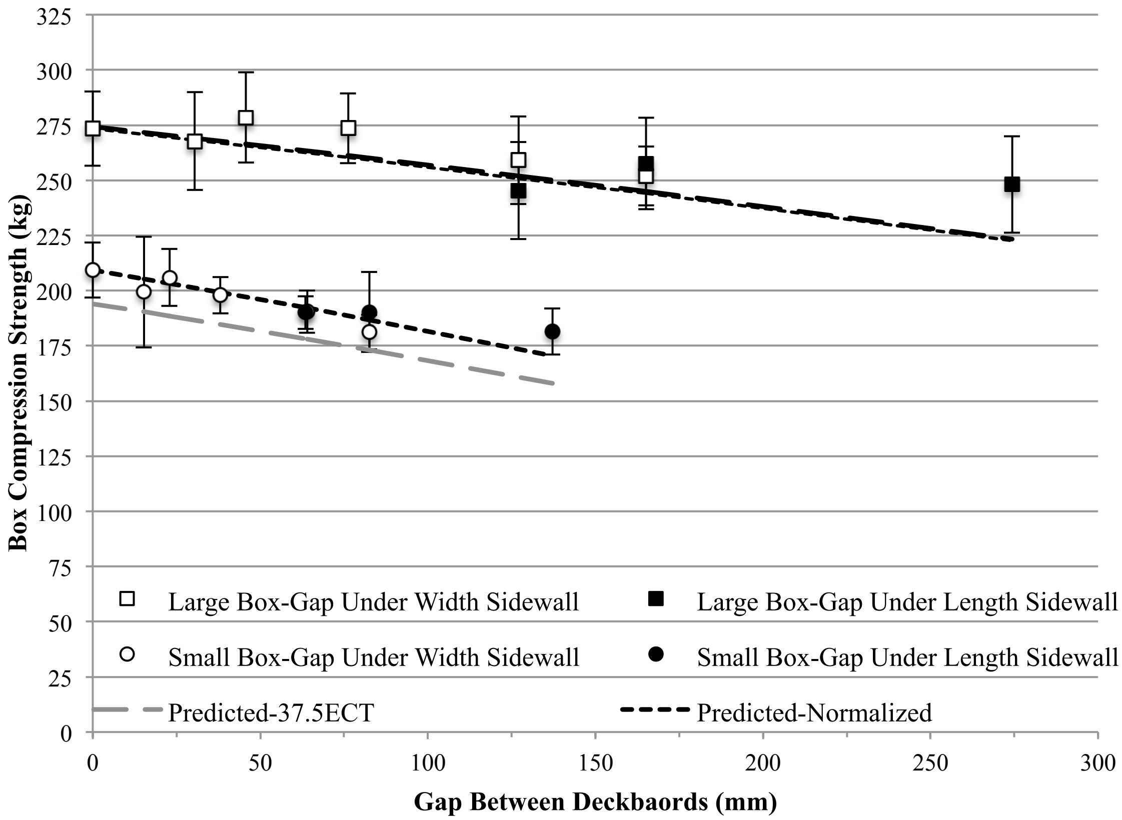

Figure 26 The effect of gaps on the compression strength of 508 mm x 305 mm x 305 mm "Large" boxes and 254 mm x 152 mm x 152 mm "Small" boxes. Grey line represents predicted values using the 37.5 ECT while the red dotted line represents predicted values normalized to 0 mm gap.

In summation, the original and modified McKee equation is highly dependent on the quality of data being input into the equation. As a result of these finding the Modified McKee looks to be a promising method for addressing a range of deckboard gaps but is not a global solution. The inherently high variation in corrugated boxes masks much of the gap effect and compared to a dedicated model. The strength of the Modified McKee is its industry friendly application. Two 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.

8 CONCLUSION

- Similar reductions in strength were found when boxes were oriented with the width and length sidewall over identical gaps.
- 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 has a similar error to the original equation with both being limited by the inherent variation in corrugated boxes. Error was further reduced by adjusting for moisture content.

9 RECOMMENDATIONS FOR FUTURE RESEARCH

Future studies can improve the accuracy of the Modified McKee Equation by revisiting McKee's simplification process (McKee 1963) and by factoring in box height according to Batelka and Smith's equation (1993). 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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Chapter 2: Effect of Pallet Deckboard Stiffness on Corrugated Box Compression Strength

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1 ABSTRACT

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 of 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.

It was found that decreasing the deckboard stiffness reduced the compression strength of a box by as much as 26.4%. Additionally, changing the location of a box relative to the stringer was found to reduce compression strength by an additional 15.3% when only two corners were directly over the stringer. The effect of gaps between deckboards was found to have a more complex interaction that decreased the effect of deckboard stiffness.

Keywords: stiffness, corrugated box, package, compression strength, pallet, unit load.

2 INTRODUCTION

Corrugated boxes are ubiquitous in today's economy [1]. A large number of studies starting in the 1950's have developed empirical models to predict the compression strength of corrugated boxes [2,3,4,5,6,7,8,9,10]. 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 [12,13,14,15].

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, which 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 2 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.

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 to the same layer of boxes on a flat platen the study found 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 compressions 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 endeavored 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 mm 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 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 [25,26,27,28,29,30]. 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 labeled “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, 29,30]. 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].

3 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.

4 MATERIALS

4.1 Corrugated Paper Board Box

Production grade samples of 254 mm x 152 mm x 152 mm Regular Slotted Containers (RSC) were used in this study. The boxes were made of B-flute 5.6 kN/mm (32 lb/in) Edge Crush Test (ECT) corrugated paperboard. The boxes were manufactured at Corrugated Container Corporation, Roanoke, VA with industry standard manufactures 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 square-ness until the glue had cooled.

4.2 508 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 to 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 mm x 152 mm x 38 mm specimens with perfect square edges (Figure 27).

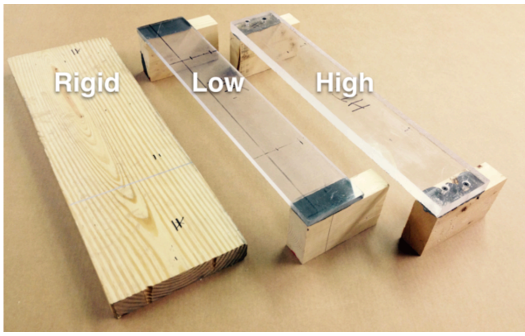

Figure 27 One of each assembled deckboard treatment

Flexible deckboard segments consisted of deckboards made from Poly (methyl methacrylate) (PMMA) commonly known as Plexiglas® (Figure 27). Decks were cut to 508 mm x 89 mm, with a thickness of 22 mm, 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 mm x 38 mm x 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 mm x 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 28).

Figure 28 High stiffness deckboard segments mounted to oriented strand board base with no span (0 mm) between deckboards.

4.3 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 due 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 center and affixed to the deckboard in the same method as the 508 mm sections (Figure 29).

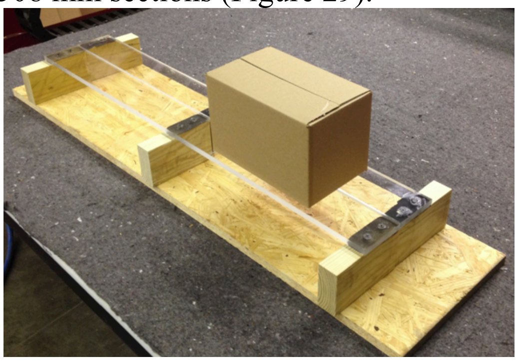

Figure 29 A photograph of full-length Medium stiffness deckboards mounted to oriented strand board base with no span (0 mm) between deckboards. Box positioned at location 1 (centered between the stringers).

5 METHODS

5.1 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 30 A 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 30). 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 setup, 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.

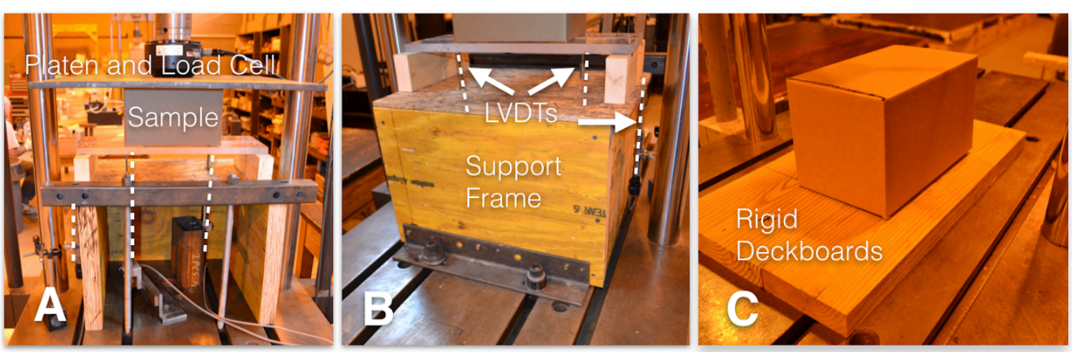

Figure 30 A) Side 1 of the test setup used to determine the effect of pallet deckboard stiffness on box compression strength. Dotted lines overlay LVDT locations. **B)** Back side of test set up. **C)** Rigid deckboard set up, no LVDTs.

The corrugated box was centered 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: Model: 244.31) equipped with 4536 Kg load cell (MTS Systems Corporation 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 30 C). 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 mm 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.

5.2 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 31). Location A was directly between two stingers and is equivalent to the testing conducted in section 4.1. For location B the box is placed so that one panel is located directly over the center stringer and the opposite side supported by the deckboard between the stringer segments. For location C the box is centered over the center stringer.

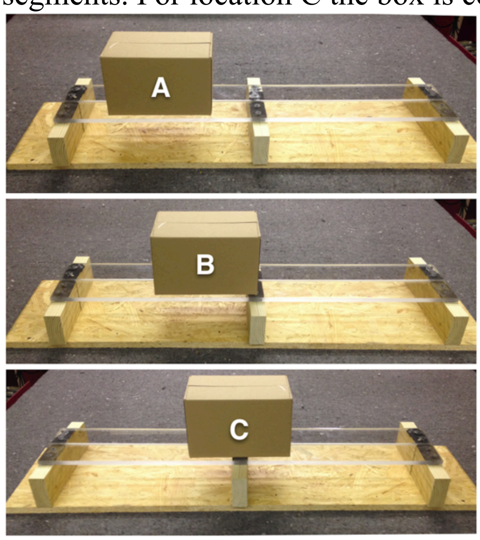

Figure 31 Picture of boxes positioned at each test location relative to the stringer.

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.

5.3 Moisture Content

Following the compression test, the moisture content (MC%) 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 (RH%) using the formula outlined by Kellicut and Landt (Equation 1) [2,34].

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

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

5.4 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 mm and 83 mm (Table 6). 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 analyze 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 (α=0.05).

6 RESULTS AND DISCUSSION

6.1 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 to 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 7). 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 32 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.

Figure 32 Front angle photograph of a box on Low stiffness deckboard. Note- corner crush opposed to the buckling along the width sidewall.

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, are causing the PMMA deckboards to twist along their central axis. Figure 33 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].

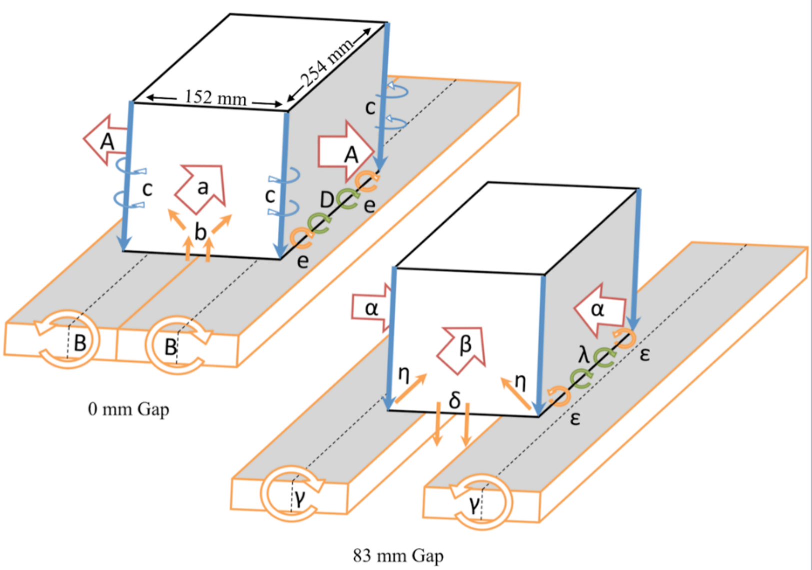

Figure 33 Illustrations of the hypothesized myriad forces acting on a box as deckboards with and without gap rotate.

Figure 33 shows the 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 edges crease 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 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 were 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 centerline 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 to 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 center 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 centerline 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 to 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 to 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 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 to other previously tested factors affecting box compressions strength such as interlock stacking which reduces strength by 45% [2], high relative humidity (90% relative humidity) which reduces strength by 57%, and long-term storage (36 days) which 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 the corrugated box design is capable of performing as required.

6.2 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 deckboards stiffness (Medium and Low) are in Table 8. 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 to the corners over the deckboard. By comparison the box 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.

6.3 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 9) 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 deck board treatments produced a decline in box stiffness of 19.9% and 61.6% compared to boxes on rigid treatment (Table 9).

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 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 10. Boxes on high stiffness deck boards, both with and without the 83 mm gap did not experience a significant change in deformation at failure compared to those on rigid deck boards. However, the deformation at failure of boxes on low stiffness deckboards increased by 82.6% and 219 % compared to the rigid deck boards when positioned over 0 mm 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 center of the deckboard deflect more than the center of the box (Figure 32) 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 center of the packaging becoming unsupported [25,26,28,29]. Figure 6 shows 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 since a box designed to have proper headspace protecting the product inside will be unable to preform 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 produce significantly greater deflections at failure.

7 CONCLUSIONS

The results indicate that deckboard stiffness and bending has 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 to 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 the gap allowed the deckboards to rotate which 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 centerline producing any number of complex interactions as the decks rotate. Box designers should consider deck board stiffness when conducting laboratory testing. However no standard method exists for adjusting safety factors or box design criteria.

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9 LIST OF TABLES

Table 6 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	

Table 7 Summary table of box compression strength resulting from various deckboard stiffness treatments at 0 mm 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

Note: Differences within the groups are determined using Tukey's HSD at α=0.05; Results not connected by same letter were significantly different.

Table 8 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

Note: Differences within the groups are determined using Tukey's HSD at α=0.05; Results not connected by same letter were significantly different.

Table 9 Summary of box stiffness resulting from various deckboard stiffness treatments at 0 mm and 83 mm Gaps between deckboards.

Deckboard Stiffness	0 mm Gap Between Deckboards				83 mm (3.25 in) Gap Between Deckboards			
	Stiffness Kg/mm (lbs./in.)	CoV (%)	Tukey's HSD	Stiffness Reduction (%)	Stiffness Kg/mm (lbs./in.)	CoV (%)	Tukey's HSD	Stiffness Reduction (%)
Rigid	46,660 (4,050)	17.1	A	------	38,090 (3,306)	13.8	B	------
High.	37,500 (3,255)	11.1	BC	-19.6	30,513 (2,648)	7.3	C	-19.9
Low	22,619 (1,963)	35.5	D	-51.5	14,610 (1,269)	18.8	E	-61.6

Note: Differences within the groups are determined using Tukey's HSD at α=0.05; Results not connected by same letter were significantly different. * box stiffness measured at corner.

Table 10 Box deformation at failure as a result of deckboard stiffness at 0 mm and 83 mm gap between deckboards. (Preload of 23 kg according to ASTM D-642).

Deckboard Stiffness	0 mm Gap Between Deckboards				83 mm (3.25 in.) Gap Between Deckboards			
	Deformation at Failure mm (in.)	CoV (%)	Tukey's HSD	As % of total box height	Deformation at Failure 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

Note: Differences within the groups are determined using Tukey's HSD at α=0.05; Results not connected by same letter were significantly different.* box stiffness measured at corner.

Chapter 3: The Effect of Reduced Flap Length on Corrugated Box Compression Strength at Various Support Conditions

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1 ABSTRACT

Corrugated paper boxes are ubiquitous and therefore consume a large quantity of wood fiber. As a result, small material savings can produce significant gains in efficiency. Reducing the length of the box flaps reduces paper without removing material from the structurally important sidewalls. However, the flaps play a significant roll in distributing load to the box sidewalls depending on support conditions. During this study, the effect of box flap length on compression strength was determined when boxes were supported, as they would be, in commercial unit loads.

The various support conditions included the gaps between pallet deckboards, flexible pallet deckboards, and misaligned versus perfectly aligned column stacks of boxes. It was found that under all support conditions the box flaps could be reduced by 25% without a significant reduction in strength or increase in deflection. This represents a 12% reduction in board area. A flap reduction of 50% caused a significant reduction in strength during various tests; however, the reduction was less than 8% in all support conditions except misaligned stacking. Therefore, in a carefully designed unit load it is possible to save approximately 24% in board area while sacrificing less than 8% of the box compressive strength. The results indicate that manufactures can reduce their packaging cost and environmental impact with little loss in vertical compression strength.

2 INTRODUCTION

The paper and paperboard industry generated $59.2 billion in revenue during 2013 alone with growth expected to continue.[1] Today, 90% of packaged products make use of corrugated paper and account for 80% of all packaging material by weight.[2,3] Paper packaging creates large amounts of waste and the mitigation of this waste is one way to increase the sustainability of operating supply chains. In 1975, the European Union devised a classification system known as the waste hierarchy. The system ranks five stages of waste management in order, from the most to the least, sustainable: prevention, reuse, recycle, recovery, and disposal.[4] The paper industry has been successful at implementing sustainable practices including the recovery of 50.1 million tons of paper being recovered compared to the 78.95 million tons manufactured in 2013.[5] Additionally, the paper used per packaged good has been reduced by 13.7% over the last decade through better design and manufacturing practices.[5] Environmental and economic factors provide compelling reasons to reduce paper usage.[6]

“Gap flapping” is a box design process based on shortening the flaps to reduce the board area of a box. The advantage of this paper savings method is that material is removed from the top and bottom of the box and not from the load carrying sidewalls. Gaur 2007 was the first to tests boxes with reduced flaps and found that smaller flaps reduced the diagonal (corner-to-corner) compression strength.[7] When unitized, vertical compression strength is more important.[8]

The disadvantage of reducing flap length is that a hole is left in the top and bottom of the box. Many products do not need full protection, so companies may choose to reduce the flap length to save on the cost of materials without changing the sidewalls and therefore not influence the vertical stacking strength. However, boxes are subjected to a wide range of shipping and storage situations that do not uniformly support to the bottom of the box.

Boxes are primarily shipped in unit loads where vertical stacking strength is key to protect the product from damage.[9] A unit load consists of packaged products on a pallet and bound together as a cohesive unit using a load containment method such as stretch wrap or strapping. Kellicut (1963) compared the compression strength of boxes on a flat platen with boxes on a pallet and found that pallets cause 12-13% loss in box compression strength.[10] Ievans 1975, Monaghan and Marcondes 1992, and DiSalvo 1999 have all found that the gap between pallet deckboards reduces box compression strength.[11,12,13] No study has explored the effects of pallet gaps on reduced flap boxes.

In a unit load, boxes may be column stacked with each box aligned directly on top of one another so that the forces are distributed directly from each box sidewall and corner to the sidewall and corner of the box below. Boxes may also be interlocked with each layer arranged in various patterns. Interlocked stacking patterns do not distribute load directly to the box sidewall. Interlocking boxes reduce the vertical compression strength of the box by 49%.[11] To date, no study has explored the vertical stacking strength of reduced flap boxes in vertical compression in various stacking configurations.

3 OBJECTIVE

The principal objective of this study is to evaluate the effect of flap length on the compression strength and deformation of regular slotted containers (RSC). The specific objectives are to evaluate the effect of reduced flaps on box compression strength when the box is supported by:

- Parallel rigid deckboards with gaps between them.
- Deckboards that bend.
- Boxes in perfectly aligned and misaligned column stacks.

4 MATERIALS

4.1 Corrugated Paperboard Box

Production samples of Regular Slotted Containers (RSC) were used in this study. The boxes were made of 14.5 kg (32 lbs.) Edge Crush Test (ECT) B-flute corrugated paperboard. The boxes were manufactured at Corrugated Container Corporation of Roanoke, VA with industry standard manufactures joints, delivered knocked down, banded, and palletized.

Two boxes sizes were used in this study, 254 mm x 152 mm x 152 mm "Small" and 508 mm x 305 mm x 305 mm "Large". For both box sizes, the flaps were trimmed to produce three reduced flap designs with 75%, 50% and 33% reduction from full flap length (Figure 34, 35). The subsequent reduction in material is shown in Table 11. The flaps of the corrugated boxes were glued with a 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 square-ness until the glue had cooled.

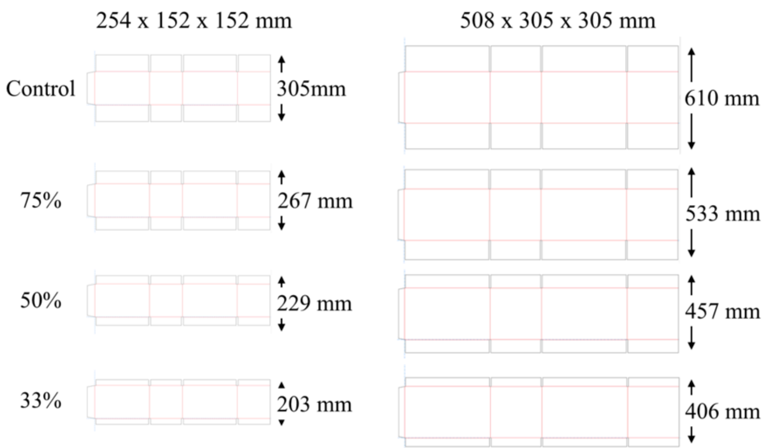

Figure 34 Engineering drawings of 254 mm x 152 mm x 152 mm and 508 mm x 305 mm x 305 mm RSC style corrugated boxes with reduced flap lengths of 75%, 50% and 33%.

Figure 35 Picture of 254 mm x 152 mm x 152 mm box from left to right: control, 75% flap, 50% flap and 33% flap.

Table 11 Summary table of box area and material weight reduction for the investigated reduced flap box designs.

Box Size	Flap length (% of control)	Board Area (cm)	Weight (g)	Material Reduction (%)
Small (254 x 152 x 152 mm)	100%	253	131	-----
	75%	223	118	12
	50%	193	100	24
	33%	173	91	32
Large (508 x 305 x 305 mm)	100%	1001	522	-----
	75%	879	458	12
	50%	758	395	24
	33%	677	354	32

4.2 Pallet Deckboards

The treatments consisted of Rigid, High, and Low stiffness simulated pallet deckboards built from materials capable of withstanding repeated testing without fatigue. The segments were constructed as follows:

"Rigid" deckboards (Figure 36) were produced using Southern Pine boards free of knots or other defects. The boards were cut to 508 mm x 152 mm x 13 mm specimens with perfectly square edges. During testing, these boards were placed directly on a flat metal platen so that the boards were fully supported and thus only subject to negligible deformation through compression of the wood fibers.

High and Low stiffness deckboard segments were made from Poly (methyl methacrylate) (PMMA) commonly known as Plexiglas® (Figure 36). The PMMA was cut to 508 mm x 89 mm, and a thickness of 22 mm for a "High" stiffness (EI=155 $N{\bullet}m^2$) segment and 13 mm thickness for a "Low" stiffness segment (EI=22.5 $N{\bullet}m^2$). The High and Low stiffness treatment were selected to duplicate the stiffness range identified in a preliminary survey of used wooden pallets. These PMMA deck segments were then mounted 89 mm x 38 mm x 127 mm Southern Pine "Stringers". Figure 36 shows the final assembly of two deckboards butted together with an oriented strand board (OSB) base.

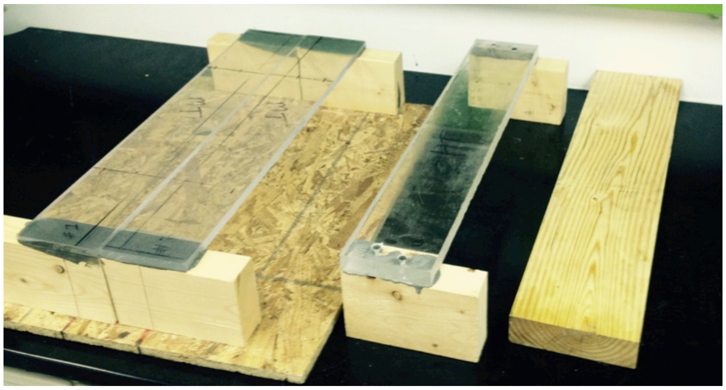

Figure 36 Simulated pallet deckboards from left to right: two PMMA “Low” stiffness deckboards mounted to base OSB with 0 mm gap between decks as prepared for testing, one PMMA “High” stiffness deckboard, and one “Rigid” treatment deckboard made of Southern Yellow Pine.

5 METHODS

5.1 Effect of Reduced Flaps on Box Compression Strength when Supported by Deckboards with and without Gaps

Two sizes of boxes (508 mm x 305 mm x 305 mm “Large” and 254 mm x 152 mm x 152 mm “Small”) were tested over the fully supported “Rigid” deckboards. The “Rigid” deckboards were first butted together to simulate a pallet with no spacing between the deckboards and then spaced apart in subsequent tests. The gap was set to 83 mm for the “Small” box and 165 mm for “Large” box to simulate the relative size and number of gaps that each box size would experience on a typical wood pallet. The box was oriented so that the width panel was centered over the gap (Figure 37). Ten replicates tested at each flap length and gap combination.

Compression testing was conducted according to TAPPI T-804 Compression of Fiberboard Containers testing standard.[14] A force was applied to the boxes at a crosshead speed of 12.5 mm/min. with a fixed platen using a Lansmont Corporation compression tester (Model: Squeezer) equipped with a 2,270 Kg load cell. The test was continued until the box had buckled on all four sides or yielded 20% compression strength from its peak compression strength. Ten replicates were tested for each flap length using 0 mm and 83 mm pallet gaps for both investigated box sizes.

Figure 37 The 254 mm x 152 mm x 152 mm box with 100% flap length centered over 83 mm gap between "Rigid" deckboards as prepared for testing in the Lansmont compression tester.

5.2 Compression Testing of Boxes on Simulated Pallet Deckboards

Two simulated pallet deckboards were butted parallel against one another (0 mm gap between deckboards) and mounted on a rigid OSB plate. Boxes were then centered on the pallet decks and tested. This test was repeated with three deckboard stiffness treatments ("Rigid", "High" and "Low"). Due to the width of the deckboard, only the 254 mm x 152 mm x 152 mm boxes were used for this study. Ten replicates of each flap length were tested on each deckboard segment.

5.3 Compression Testing of Perfectly Aligned and Misaligned Column Stacked Boxes

For the column stack testing, the boxes were positioned two-high on a rigid platen. Perfectly aligned column stacks were arranged so that all four vertical edges aligned perfectly while the misaligned stack had the upper box offset from the bottom box by 25 mm (1 in.) side-to-side and 25 mm front-to-back (Figure 38). Five replicates were tested for each flap length using aligned and misaligned columns for both investigated box sizes.

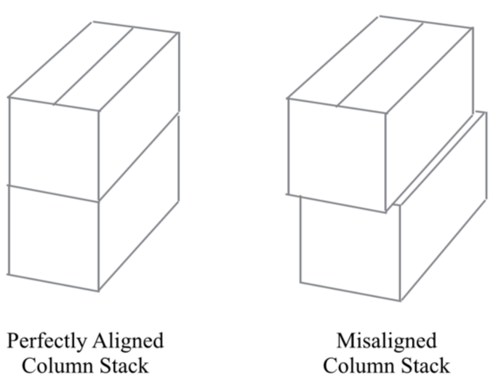

Figure 38 Diagram of perfectly aligned column and 25 mm misaligned column stack.

5.4 Moisture Content

For all of the tests, a sample was taken from every box after testing in order to determine moisture content according to TAPPI T-412.[15] Once the moisture content was established, the compression strength of the box was adjusted according to the moisture equilibrium of paper at standard temperature and relative humidity of 23 °C and 50% relative humidity using the Kellicut and Landt equation (1).[10,16]

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

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

6 RESULTS AND DISCUSSION

6.1 Effect of Gaps Between Pallet Deckboards on the Compression Strength of Boxes With Reduced Flap Lengths

An analysis of the 254 mm x 152 mm x 152 mm "Small" and 508 mm x 305 mm x 305 mm "Large" boxes supported by a 0 mm gap between deckboards indicated that flap length had a significant effect on box compression strength. The compression strength of the "Large" box significantly decreased (-18.0%) when the lap length was reduced to 33% . The compression strength of the "Small" boxes significantly decreased, -7.9% and -10.5%, when the lap length was reduced to 50% and 33%, respectively. The flap reduction produced a significantly different strength reduction in each of the two boxes, -18% for the "Large" and -10.5% for the "Small" for the 33% flap, indicating that the effect changes with box size.(Figure 39)

After completing testing with fully supported sidewalls (0 mm gap) the deckboards were spaced to 83 mm and 165 mm for the "Small" and "Large" box, respectively. The gap had a significant effect on box compression strength for both box sizes, which confirms previous findings of Ievans 1975, Monohgan and Marcondes 1992, and DiSalvo 1999.[11,12,13]

When the "Large" boxes were tested over 165 mm gap a significant reduction in strength occurred at both the 50% (-7.2% reduction) and 33% (-17.0% reduction) flap lengths (Figure 39). By contrast, there was no effect on the "Small" boxes.

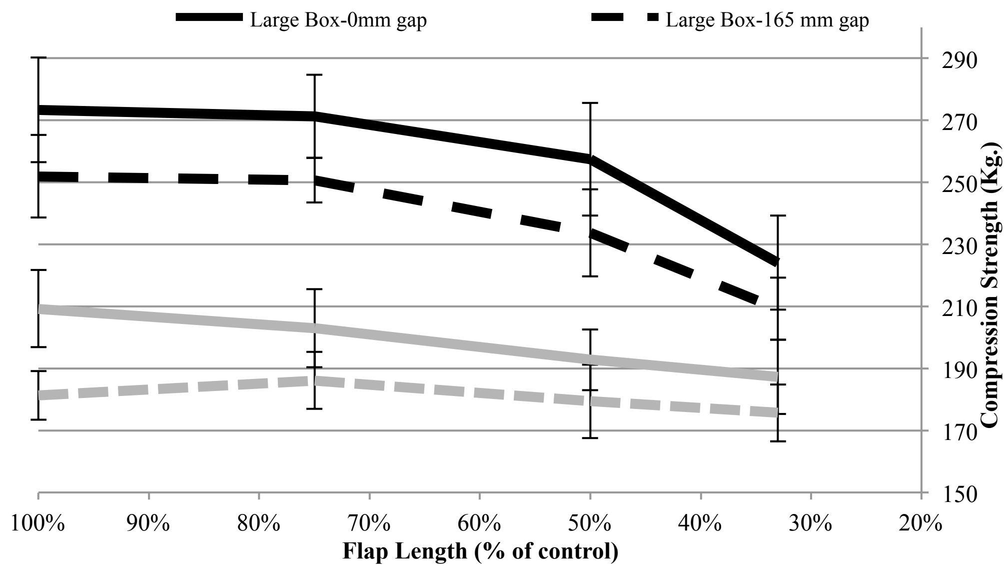

Figure 39 Compression strength of 508 mm x 305 mm x 305 mm "Large" and 254 mm x 152 mm x 152 mm "Small" boxes with varying flap length supported by deckboards with 0 mm and 83 mm gap. Whiskers represent standard deviation.

6.2 Effect of Reduced Flaps on the Box Compression Strength when Supported by Deckboards of Varying Stiffness.

Only the smaller 254 mm x 152 mm x 152 mm boxes were used to test the interaction between reduced flaps and deckboard stiffness. It was found that both characteristics had a significant, but inconsistent, effect on box strength (Figure 40). Boxes on "Rigid" deckboards experienced a significant reduction when the flaps were trimmed to 50% and 33% of their original length (section 6.1 above) while boxes on "High" stiffness deckboards experienced no change between reduced flap treatments. Boxes on "Low" stiffness deckboards produced a far more inconsistent result with the 75% flap being significantly stronger (+10.5%) than the 100% flap length. 50% flaps produced no significant change and 33% flap lengths reduced compressive strength by -11.2%.

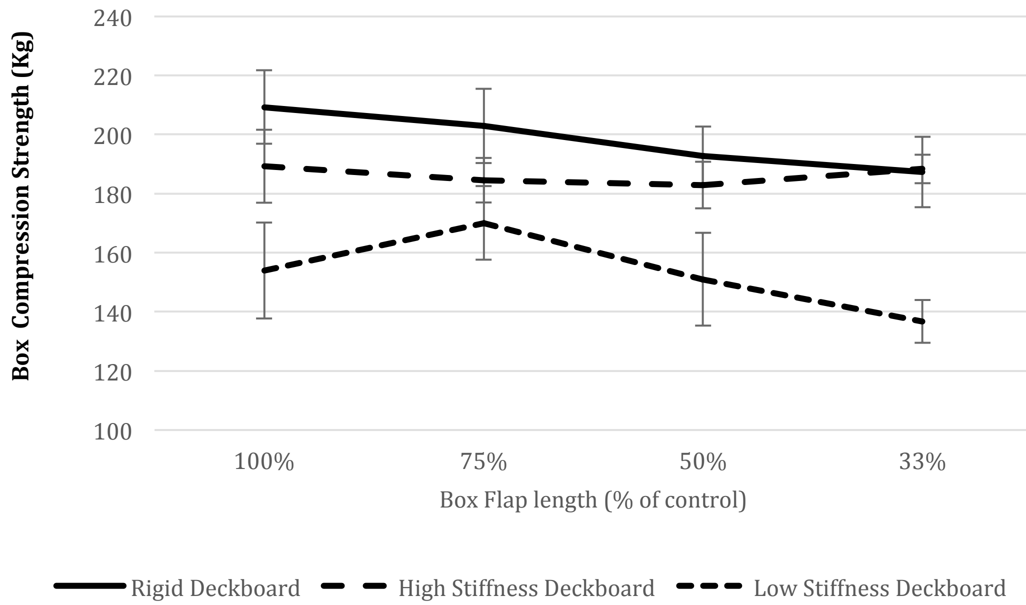

Figure 40 Compression strength of 254 mm x 152 mm x 152 mm boxes with reduced flaps supported by deckboard of varying stiffness.

It was observed during testing that the PMMA deckboards twisted during the test. The box corners were beyond the centerline of the deckboard causing the board to twist when a force was applied. The twisting was almost imperceptible in the "High" stiffness deckboards and clearly visible in the "Low" stiffness deckboards. Preliminary studies have established that the transference of forces from the flaps to the sidewalls is complex. There is an interaction between deck stiffness and flap length where shorter flaps can be used in boxes on lower stiffness deckboards. Further research is needed to quantify the effects of deckboard twisting and the distribution of forces along the flaps and sidewalls.

6.3 Effect of Reduced Flap Length and Box Alignment on Box Compression Strength and Deformation

6.3.1 Compression Strength

Boxes in misaligned column stacks were significantly weaker (50-55% reduction) than all perfectly aligned columns. This finding agrees with previous studies:

- Ievans 1975 found a 49% reduction in strength for misaligned 3 high stacks. [11]
- Kellicut 1963 found a 36% at 13 mm offset in 3 high stacks. [10]
- Park 2010 predicted 44% reduction in strength the same 25 mm offset. [17]

Flap length had a significant effect on the compression strength of perfectly aligned and misaligned column stacks. Both "Large" and "Small", perfectly aligned, boxes lost strength only when the flaps were reduced to 33% of control.

Misaligned stacks of "Large" and "Small" boxes experienced a significant reduction in strength when the flaps were reduced to 50% and 33% of control (Table 12). The compounding losses caused by misaligned stacking are the result of vertical stacking forces being transferred through the box flaps and not directly from one sidewall to another. During commercial use, it is nearly impossible for a unit load to maintain a perfectly aligned stack. Therefore, flap reduction design should assume misalignment and design boxes accordingly.

Table 12 The effect of flap length on compression strength in misaligned and column stack boxes.

Box Size	Stacking Pattern	Flap Length (% of control)	Compression Strength (Kg).	Strength Reduction	Tukey's
Large (508 x 305 x 305 mm)	Perfectly Aligned	100%	237.7 (6.61)	-----	A
		75%	243.6 (4.04)	2.5%	A
		50%	233.6 (8.18)	-1.7%	AB
		33%	207.5 (7.52)	-12.7%	B
	Misaligned	100%	118.5 (4.6)	------	a
		75%	115.0 (9.31)	-3.0%	a
		50%	82.4 (3.63)	-30.5%	b
		33%	69.8 (7.16)	-41.1 %	c
Small (254 x 152 x 152 mm)	Perfectly Aligned	100%	185.1 (5.76)	-------	A
		75%	183.4 (7.42)	-0.9%	AB
		50%	174.8 (4.76)	-5.6%	AB
		33%	160.0 (11.41)	-13.6%	B
	Misaligned	100%	83.1 (5.56)	-------	a
		75%	79.8 (5.57)	-4.1%	a
		50%	48.6 (4.68)	-41.6%	b
		33%	37.0 (13.32)	-55.5%	c

Note: values in parentheses are Coefficient Variation values. Note: Differences within the groups are determined using Tukey's HSD at $\alpha=0.05$; Results not connected by same letter were significantly different.

Similar letters for the Tukey analysis indicate no significant difference using $\alpha=0.05$.

6.3.2 Stack Deformation

For "Large" 508 mm x 305 mm x 305 mm perfectly aligned boxes a significant increase in total stack deflection of 6.4% was observed when the length of the flaps was reduced to 33% (Figure 41). Perfectly aligned 254 mm x 152 mm x 152 mm "Small" boxes had a significant increase in deflection of 15.8% when the flaps were reduced to 50% or more (Figure 42). The results indicate that flap reduction in commercial use must account for the impact of increased deformation to the box headspace.

The misaligned stack did not distribute the load directly down the sidewalls of each box but instead pressed directly on the flaps resulting in a large increase in deflection as well as a concentration of stress at intersection of box sidewalls (Figure 43). Contrary to the results observed for the perfectly aligned stacks, the change in the flap length did not cause any significant change in the stack deflection of the misaligned stacks. This was mostly due to the large increase in standard deviation.

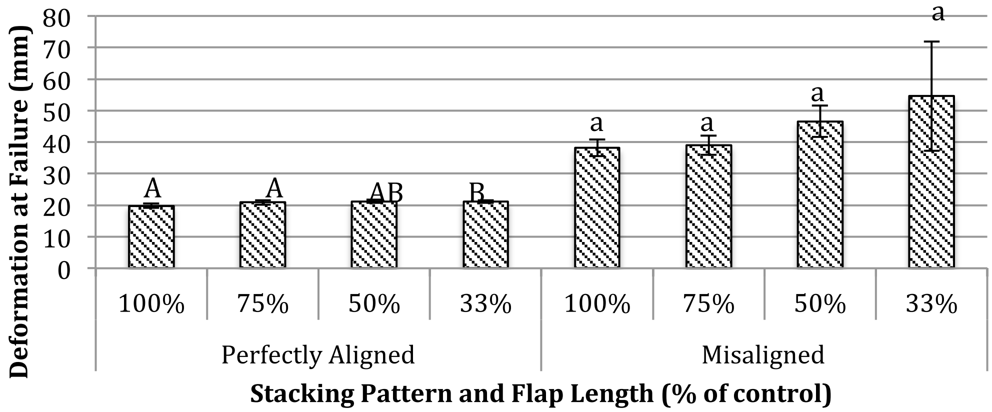

Figure 41 Deflection of 508 mm x 305 mm x 305 mm "Large" boxes with varying flap lengths in perfectly aligned and misaligned column stack.

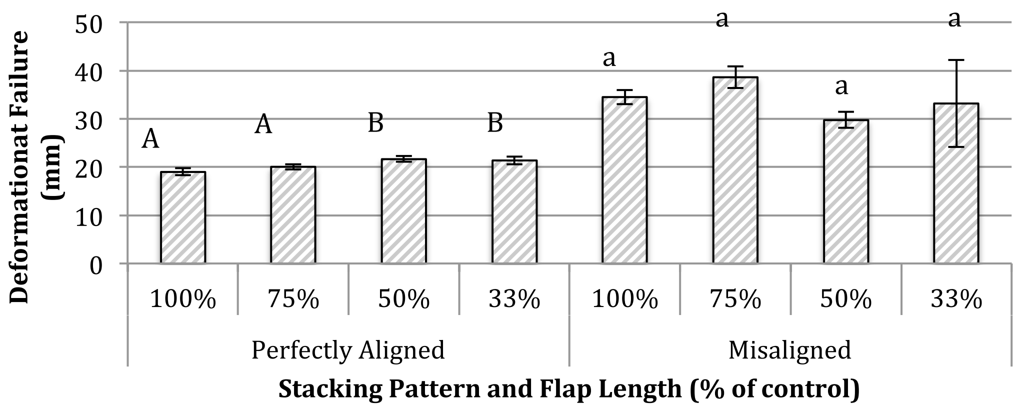

Figure 42 Deflection of 254 mm x 152 mm x 152 mm "Small" boxes with varying flap lengths in perfectly aligned and misaligned column stack.

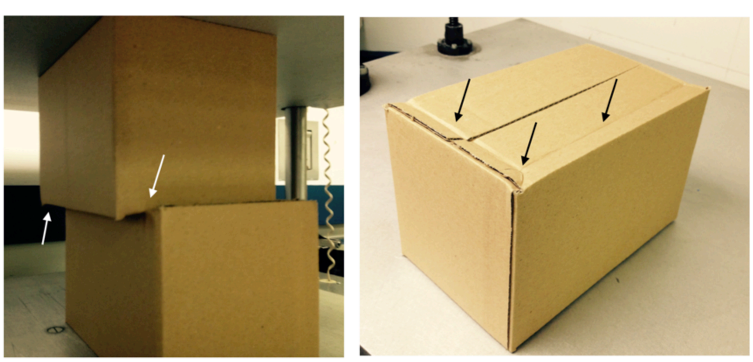

Figure 43 Left: Photograph of "Small" boxes in 25 mm misaligned stack with large amount of vertical deflections. Right: Picture after testing of damage caused by misaligned stacking.

7 CONCLUSION

Compression Strength

1. Reduction of box flap length did not have a significant effect on the box compression strength when the flaps were reduced by 25%. This represented a 12% reduction in board area.
2. A flap reduction of 50% caused a significant reduction in strength during various tests; however, the reduction was less than 8% in all scenarios except misaligned stacking. Therefore, in a carefully designed unit load it is possible to save 24% in material while sacrificing less than 8% of the box compressive strength.
3. Flap reduction has a greater effect on the compression strength of larger boxes.
4. The interaction between flap length and deckboard bending indicates that smaller flaps can be used on boxes supported by less stiff deckboards.
5. Flap reduction produced a greater strength loss when boxes were in a misaligned in a column stack than when the boxes were in an aligned column stack.

Deformation

6. Boxes in all misaligned stack situations had a significantly greater deflection at failure than any of the column stacked situations.
7. A 50% reduction in flap length increased the deformation at failure by as much as 16%.

8 ACKNOWLEDGMENTS

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Chapter 4: Application of Beam on Elastic Foundation to the Interaction Between a Corrugated Box and Pallet Deckboard

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1 ABSTRACT

When unitized, the compression strength of the corrugated box will be affected by the deflection of the pallet deckboards. Current box compression safety factors do not accurately account for this effect, resulting in costly over design or failures. In this study the theory of beam-on-elastic foundation was used to model stress along box/deckboard interface and predict box failure.

The model was capable of predicting the distribution of stress along the boxes' length sidewall and the deflection of the deckboard. However, the model was not capable of predicting the box compression strength at failure due to horizontal forces imparted on the width sidewall and asymmetric strength caused by the manufacturers joint. The beam-on-elastic foundation model enables box designers and pallet designers to collaborate on holistic designs that are structurally, economically and sustainably optimized.

2 INTRODUCTION

Currently there are approximately 32 to 38 million tons of corrugated paper and approximately two billion pallets in circulation throughout the United States.[1, 2, 3] Such a large volume means that small improvements in performance or material reduction results in compelling cost and sustainability benefits. Corrugated boxes are often shipped in a unit load where the pallet and box must work together to facilitate shipping and distribution. Understanding how the pallet and box interact and applying this understanding to their design will lead to more efficient supply chains.[1]

In a unit load, the corrugated boxes and pallet deckboards deform under load to a degree that is mutually dependent on the properties of each. This relationship is in many ways represented by the beam-on-elastic foundation models developed for the early rail industry where railroad tracks deformed over soft ground. In this case, the pallet deckboard represents the rail and the box represents the ground. The first example of beam-on-elastic foundation modeling was developed in 1867 by E. Winkler.[4, 5, 6] The simple elastic foundation model consisted of a foundation that had been subdivided into many discrete springs [4, 5, 6, 7]. Föppl (1909) noted that the Winkler model does not accurately reflect the true nature of soil due to a lack of shear between the discreet spring segments. [5, 7, 8]

Filonenko-Borodich (1940) addressed the limits of the Winkler foundation by connecting the springs with membranes under tension. [7, 9] Hentényi foundation (1946) took a slightly different approach by connecting the springs with a beam that provided flexural rigidity thus transferring some of the compression to adjacent spring elements.[10] Hentényi also developed a number of specialty solutions to cases such as railroad tracks crossing an underground mineshaft or a foundation consisting of differing moduli topsoil and subsoil. [5, 11]

The Pasternack foundation is similar to the Hentényi foundation, however, the beam ties the springs together using only the shearing component. [5, 10, 12] Finally, in 1964 A. Kerr developed the generalized foundation consisting of a Winkler foundation on top of

Pasternack foundation which is very similar to the multilayered approach produced by Hentényi.

Beam-on-elastic foundation models are applicable to a wide range of scenarios outside the traditional rail and subsoil example. Yoo was the first to apply the theory of beam on elastic foundation to deckboards and boxes. This work was novel in that it flipped the box and pallet deckboard relationship upside down, treating the box as the elastic foundation over which the beam was compressed.[13] The model was able to predict the compressive stress distribution between the package and pallet deckboard. However, several distinct challenges were encountered with boxes and pallet; namely, difficulty determining correct boundary conditions, accounting for the inconsistent stiffness of the box along its length, and the lack of continuous contact between box and pallet, known as "load bridging". [13, 14, 15]

The previous research presents an opportunity to increase the understanding of box-pallet interactions, including pallet deck deflection, box deformation, compressive stress distribution and box failure. By addressing the aforementioned challenges, it is possible to develop a general model of the distribution of pressures within a unit load. The practical implications of such a model are the ability to identify potential package failure points before a product launch and to optimize the packaging design. In both scenarios, a compelling economic and sustainability benefit exists. The cost of empty packaging within the unit load is significantly greater than the cost of a pallet. Modeling the interaction between pallet and packaging is applicable to pallet design and will aid in reducing packaging spend.

3 OBJECTIVE

In this study the theory of beam on an elastic foundation will be applied to corrugated boxes on pallet decks. This model will be used to: 1) predict the distribution of stress along a box sidewall when the deckboards are of differing stiffness. And 2) predict the box compression strength at failure when the deckboards are of differing stiffness.

4 MATERIALS

Regular Slotted Containers (RSC) sized 254 mm x 152 mm x 152 mm were cut from 32 edge crush test grade corrugated paper. The boxes were conditioned according to ASTM D4332 to 50% relative humidity and 23^0C. [16]

The boxes were tested on three different surfaces. The control consisted of a fully supported flat rigid metal platen. The non-rigid test surfaces consisted of pallet segments with two different stiffness deckboards cut from Polymethylmethacrylate (PMMA). Compared to wood, PMMA decks are far more consistent and less susceptible to fatigue after repeated bending. The decks were 22mm thick boards (EI=155 N•m2) and 13mm thick boards (EI=22.5 N•m2). These thicknesses were chosen to reproduce "High" and "Low" EI values identified by a preliminary study as being similar to used wood pallet deckboards. "Decks" were cut to 508 mm long by 152 mm wide and glued to 89 mm square by 38 mm thick spacers that simulated pallet stringer segments. Two of these deckboard stringer segments were then butted against each other and mounted to an oriented strand board base (Figure 44).

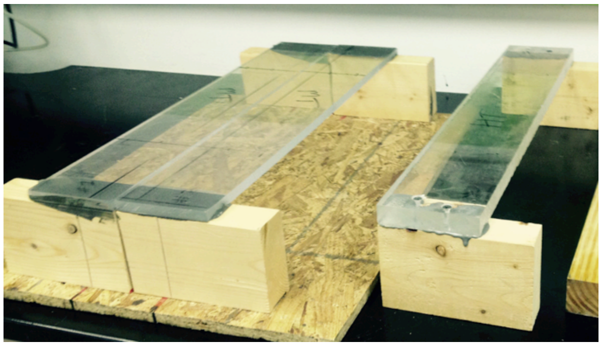

Figure 44 Left: two "Low" stiffness deckboards assembled in final testing configurations. Right: single "High" stiffness deckboard not in final test assembly.

5 METHODS

5.1 Model Development - Beam on Elastic Foundation

Beam-on-elastic foundation is in essence the combination of Hooke's Law and the Euler-Bernoulli static beam equation (1). Hooke's Law is used to describe an elastic foundation such as a box and the Euler-Bernoulli static beam equation is used to describe the shape and deflection of a pallet deck. Hooke's law describes a spring subjected to a force (p) causing a deflection (y) at a rate defined by the spring constant (k). [5]
Beam on elastic foundation models denote this as:

$$p = ky \tag{1}$$

k is the "modulus of the foundation" and when multiplied with the vertical deflection (y) produces a force (p).

Euler-Bernoulli static beam equation (3) describes the load (q) applied to a beam of stiffness (E) and moment of inertia (I), which will produce a displacement of (y) at any given point along the beam (x).

$$EI\frac{d^4y}{dx^4} = q(x) \tag{2}$$

Two distinct challenges are presented by the application of elastic foundation modeling to corrugated boxes on pallets deckboards. First, the beam is traditionally compressed into the foundation and therefore it becomes simpler to model the box-pallet relationship upside down as shown in Figure 45 (left). Second, the deckboard is not uniformly loaded (Figure 45 right) and thus the appropriate model for loaded and non-loaded segments are different and must be combined to produce the final shape of the entire deck. In this case, non-loaded segments are defined by the Euler-Bernoulli static beam equation and the loaded segments are defined by elastic modeling.

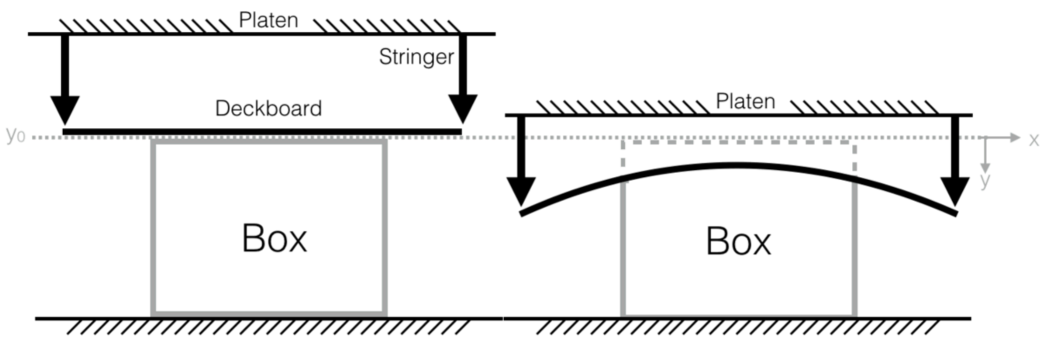

Figure 45 Left: Box and deckboard with zero load in upsidedown configuration (per the model and not as tested). Right: Deckboard is loaded and the box is compressed vertically to generate a deflecting deckboard over a deformed foundation.

For non-loaded segments, the Euler-Bernoulli equation can be used to determine the shape of any given non-loaded section of beam. The deformation at any point along the beam y(x) can be described with a fourth degree polynomial, namely P_0, P_1, P_2, and P_3. P_0 defines the initial y coordinate and therefore does not affect the final shape of the beam. Equation (4) can also be written as follows;

$$y(x) = P_3x^3 + P_2x^2 + P_1x + P_0 \tag{3}$$

For the loaded segments, the elastic foundation also has four degrees of freedom but they are derived differently. The general equation (5) utilizes a set of constants C_0, C1, C_2, C_3, C_4, in addition to F_1, F_2, F_3, and F_4, which are formulas based on the EI and k values of the foundation.[5] Unlike equation 4, y(x) is the deformation of the box and not the deflection of the beam.

$$\begin{aligned} &y(x) = C_0 + C_1F_1 + C_2F_2 + C_3F_3 + C_4F_4 \\ &\textit{where}: \\ &F_1(\lambda x) = \cosh\lambda x \cdot \cos\lambda x \\ &F_2(\lambda x) = \frac{1}{2}(\cosh\lambda x \cdot \sin\lambda x + \sinh\lambda x \cdot \cos\lambda x) \\ &F_3(\lambda x) = \frac{1}{2}\sinh\lambda x \cdot \sin\lambda x \\ &F_4(\lambda x) = \frac{1}{4}(\cosh\lambda x \cdot \sin\lambda x - \sinh\lambda x \cdot \cos\lambda x) \end{aligned} \tag{4}$$

Due to the fact that the beam and the foundation both influence the others shape it is necessary to include a final “characteristic” factor (λ) per equation (6) to complete the general solution (5).

(6)

$$\lambda = \sqrt[4]{\frac{k}{4EI}}$$

Elastic foundation models usually assume the foundation is homogeneous, but in the case of a box, there are three distinctly different regions with differing k values across the box length. The first region is the sidewall, which spans the majority of the box length. The second region is comprised of the box corners, which are known to be of greater stiffness than the sidewall. [17] The third region is the center-most region, where the deckboard deflects more than the box sidewall, resulting in an additional non-loaded region known as "load bridging". Load bridging may or may not be present depending on the stiffness of the beam and the foundation (Figure 46 D).

The lack of a homogeneous foundation means that the beam will be subjected to either three or four different regions in the foundation. These include the non-loaded distance between the stringer and the box, the region under the box corners, the region under the box sidewalls, and a possible central region of load bridging where the beam is no longer in contact with the box (Figure 3). Each loading region influences the beam differently and requires a different value for C_1, C_2, C_3, C_4, F_1, F_2, F_3, and F_4, (Figure 3) while any segment not in contact with the foundation will require P_1, P_2, and P_3 (Figure 2 A and D).

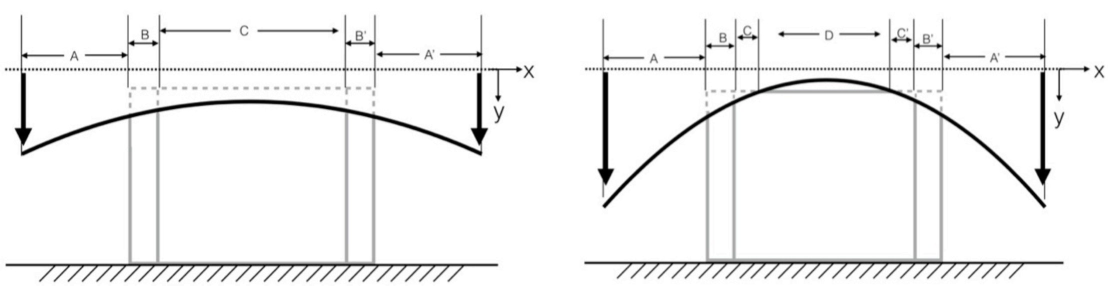

Figure 46 Diagram of a beam bending over an elastic foundation (box) with force provided at the stringer location (Black arrow). Left: C indicates lower stiffness sidewall region and B indicates higher stiffness region at the corners. Right: D indicates area of "load bridging" where the beam does not make contact with foundation.

Generating the proper shape of a beam for any given foundation and beam combination requires the segments to be stitched together. The boundary conditions at the intersection of any two regions must meet smoothly, such that the deflection, slope, and shear are equal (Figure 46). This process significantly reduces the number of necessary calculations. Determination of beam shape is facilitated by the fact that the beam is symmetrical thus A and A' will be equal but opposite (Figure 46).

The above-mentioned equations were coded using java script. The software model required four inputs. First, the outer box dimensions including box height to which the value for y_0 is set. Second, sidewall thicknesses are required. Third, the software requires the box k values which can be obtained from the load-deflection curve of boxes tested under the standard TAPPI 804 method.[18] Fourth, the software requires the rotational stiffness at the stringer and deckboard EI. The rotational spring rates and EI are obtained experimentally using free end deckboards in ASTM D3043 3-point bending and deckboard with ends affixed to the stringers and oriented strand board base (described below) in ASTM D3043 4-point bending.[19]

The model outputs included the forces P_0, P_1, P_2, and P_3 values for the non-loaded regions of the beam. The bending moment for the non-loaded regions will be equal to that of the rotational modulus at the stringer and deckboard connection. The model will also output C_1, C_2, C_3, C_4 values for each of the four loaded regions where the deckboard comes in contact with the foundation. Of the four regions, two are always symmetrical with the outermost having higher k values due to the strength of the box corners.

As mentioned previously, elastic modeling does not account for separation between the beam and foundation and assumes that the deckboard is affixed to the box. In the event the model generates a region of negative stress at the middle of the box (i.e. load bridging), the deflection will be above the y_0 origin. A region above the y_0 origin will produce a negative stress in the model; therefore, the forces in region are ignored. The deckboard shape within the load-bridging region can then be modeled in the same fashion as the other non-loaded regions but with boundary conditions matching those of the adjacent regions.

The final output is a predicted distribution of force along the beam and foundation. The beam shape can then be validated with compression testing and measuring pressure between the pallet segment and the package.

5.2 Model Development – Predicting Maximum Load

The model was used to predict the compression strength of the box at failure. As described above, the model outputs a stress distribution; however this can be modified to produce a ratio of box failure loads. To do this, a stress value needed to be assigned to a point along the length of the model, from which all the other stress could be calculated. This is possible because the model produces a distribution of stresses that maintain the same ratio regardless of the assigned value. The remaining stresses can then be calculated and when summed they produce a theoretical load.

To calculate the predicted load, a point must be selected that reflects the failure of the box and that can be compared between each of the load conditions. Previous studies have theorized that box failure occurs when a critical buckling load is reached at the box corner.[17, 20] Therefore, he “end-wall” of the model (which includes the width sidewall and corner) was selected as the location at which the same arbitrary stress would be assigned regardless of support condition.

The model was then used to calculate the remaining stresses along the sidewall for each support condition, which when summed would produce a predicted load at each support condition. To compare the measured failure data to the predicted value it was necessary to generate a “failure ratio”. To do this, the predicted load on High and Low stiffness support conditions were divided by the predicted load on rigid support. This ratio could then be compared with the measured "failure ratios".

5.3 Deckboard Bending Stiffness

Beam-on-elastic foundation modeling requires both beam stiffness and end conditions to predict the shape of the beam under load. For the High and Low stiffness deckboards, the EI values were generated using the Three-point bending test with free ends (ASTM D3043 Method A).[19] Three-point EI values do not provide sufficient information for the model to predict the shape of the beam because this method does not measure the rotational modulus of the deckboard stringer connection.

A fixed end model assumes the slope is zero at the connection between the deckboard and the stringer. However, a truly fixed connection is nearly impossible to build and therefore accurate modeling must include the effect of connection's rotational modulus. While the pallet segments were assembled with the intent of having "fixed ends", preliminary testing found that the deckboard stringer connection was not truly fixed and some degree of rotation was occurring at the connection.

A modified Four-point bending test (ASTM D3043 Method B) was used to determine the rotational modulus at the connection.[19] The span between load points was 254 mm, which is equal to the length of the box being tested. The difference between the Three-point and Four-point bending was then used to determine the rotational modulus of the connection. These resulting EI and rotational modulus values were inputs to the software.

5.4 Pressure Mat and Compression Testing

Compression testing was conducted using a Lansmont compression testing machine equipped with a 4536 kg load cell (Lansmont Corporation Model: Squeezer) per TAPPI 804. [18] A 1060 mm x 640 mm I-Scan® pressure film sensor (Tekscan lnc. Model # 5315) was used to record the distribution of pressure between the box and the pallet decks (Figure 47). The mat consisted of a top and bottom polyester film with a grid of semi conductive ink laminated between them. A voltage is applied to the mat and zeroed to a base resistance. When force is applied to the mat, the electrical resistance of the semi conductive ink decreases and the pressure can be determined. The pressure sensor had a 28-648 kPa (4-90 psi) range with a "sensel" size of $10mm^2$ and sensel density of 0.3 sensels/cm^2. Any change in voltage is recorded using the I-Scan® pressure analysis software, which outputs a data matrix with each data point correlating with a sensel. Prior to testing, the pressure mat was calibrated at 69 kPa using a pressurized air bladder. The calibration step eliminates variations caused by wear and age. During testing, the pressure mat software records data at 100 "frames" per min.

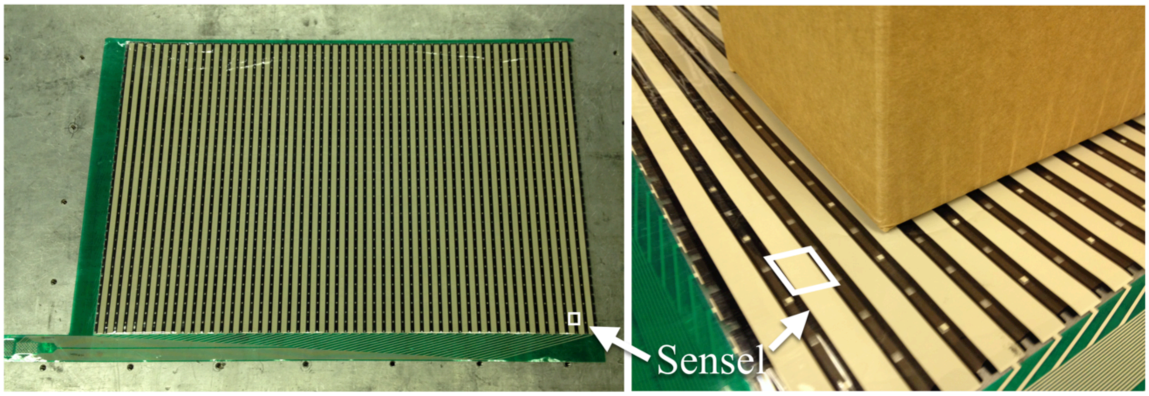

Figure 47 Image of iScan pressure mat with sensel higlighted. The realtively large sensel size alows easy alignment of the box on the mat wich is required for accurate measurement.

In the early portion of the load-deflection curve, the box flaps and creases are the source of significant variation in deflection and stress. To eliminate this variation, data was collected once every one hundred frames between half of the maximum load and the maximum load. Each frame produced a single data matrix output of the stress distribution between the box and pallet decks (Figure 48 left). This was repeated for each of the ten boxes on each of the three support conditions (fully supported, High-stiffness, and Low-stiffness deckboards).

Beam-on-elastic foundation is limited to a two-dimensional model. Therefore, the data matrix (Figure 48 left) was summed along the box width to produce a two-dimensional snapshot of the box pressure at any given sensel of the length sidewall (Figure 5 left and middle). The blue bars are significantly greater as they represent the sum of stress at one sensel of length and therefore capture the entire 152 mm width end-walls and box corners. This process was repeated for each of the frames captured. The data was then normalized at each box compressive load to generate an image of the stress distribution along the box length. Normalization was accomplished by dividing the total stress (at one frame) by the compressive load on the box (at the same frame) to generate a percentage of stress per inch. This step allowed for the comparison of stress distribution between any boxes at any compressive load (Figure 48 right).

All boxes have a “manufacturer’s joint” in one corner where two sidewalls meet and form the tube or body of the box. The manufacturer’s joint is two layers thick of corrugated material and is comparatively stronger than the other corners and produced large variations in sidewall pressure. In Figure 48, the far left image of the pressure mat shows a spike in stress (black sensel) at the lower left corner. As a result, there were large differences in pressure of the end-wall as shown by the blue bars in Figure 48 (middle). To account for the asymmetry, the 16 sensel wide data set was split down the middle and each sensel was averaged with its mirror. For example, in the middle image of Figure 5, the far left sensel, or sensel 1 (far left blue bar) would be averaged with sensel 16 (far right blue bar Figure 48 middle). This was repeated with sensel 2 and 15 and so on producing a symmetrical normalized histogram (Figure 48 right) showing the symmetrical and normalized distribution of stress to the two-dimensional box. Again, this process was repeated for each of the ten boxes on each of the three support conditions (fully supported, “High” stiffness deckboards, and “Low” stiffness deckboards).

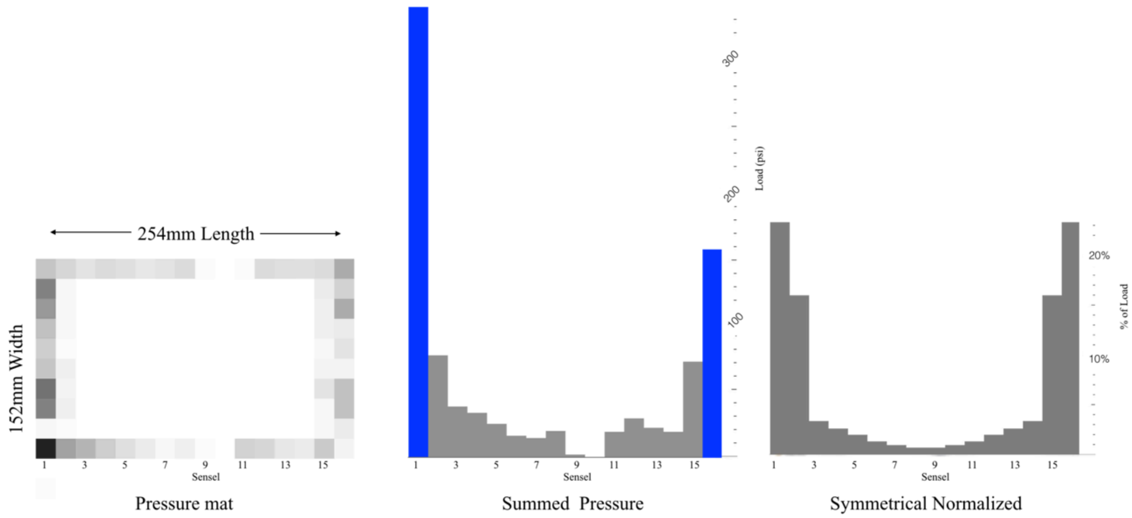

Figure 48 Simplified overview of pressure mat data processing steps. Left: top down view of pressure mat output image of a single box near failure (dark color represents greater stress). Middle: sum of pressure of the same box viewed from the length panel (blue indicates box width sidewall 10 sensels deep). Right: Average % load per sensel of all boxes with normalized data. Note: All images are 16 sensels wide.

6 RESULTS AND DISCUSSION

6.1 Modeling the Distribution of Stress

Figure 49 shows the normalized and symmetrical results for each of the three support conditions. Starting with the "end-wall" which consists of the width sidewall and corners, the pressure mat data shows the end-wall to be approximately two sensels wide. The finding suggests that the end-wall is functionally thicker than expected, especially given that care was taken to place all sidewalls directly over the sensels and not between them (Figure 48 left). Analysis of the top-down pressure mat data suggests that the high strength of the corner, where the length and width sidewalls brace each other, extends two sensels in each direction or approximately 7-18 mm. Additionally, some level of end-wall deformation and/or load transfer to the minor flap occurred along the end-wall which added the stress at sensel regions 2 and 15. Boxes on "High" and "Low" stiffness deckboards also had a two sensel wide end-wall, however, the deflection of the deckboard resulted in a gradient across the end-wall (Figure 49).

Moving inward from the end-walls, Figure 6 shows a distinct change in the pattern of stress within the sidewall of the box as the deckboard stiffness decreases. Fully supported boxes had consistent stress and thus a consistent percentage of load across the sidewall. High and Low stiffness support conditions resulted in clear reduction in stress being transferred to the sidewall and therefore the end-walls were responsible for carrying a larger % of the load. Boxes on Low stiffness decks also had a complete lack of stress along the center of the span, confirming the occurrence of "load bridging"; the phenomenon originally coined by Fagan (1982).[14]

When comparing the stress distribution for each of the three support conditions it is clear that reductions in deck stiffness resulted in decreased stress at the sidewall and increased stress at the end-wall. The variation in stress at the end-wall was greater than the sidewall due to the fact that the end-wall accounts for variation in the width panel of the box and variation caused by the manufacturer's joint. Even so, the variation at any given sensel was fairly consistent regardless of support condition.

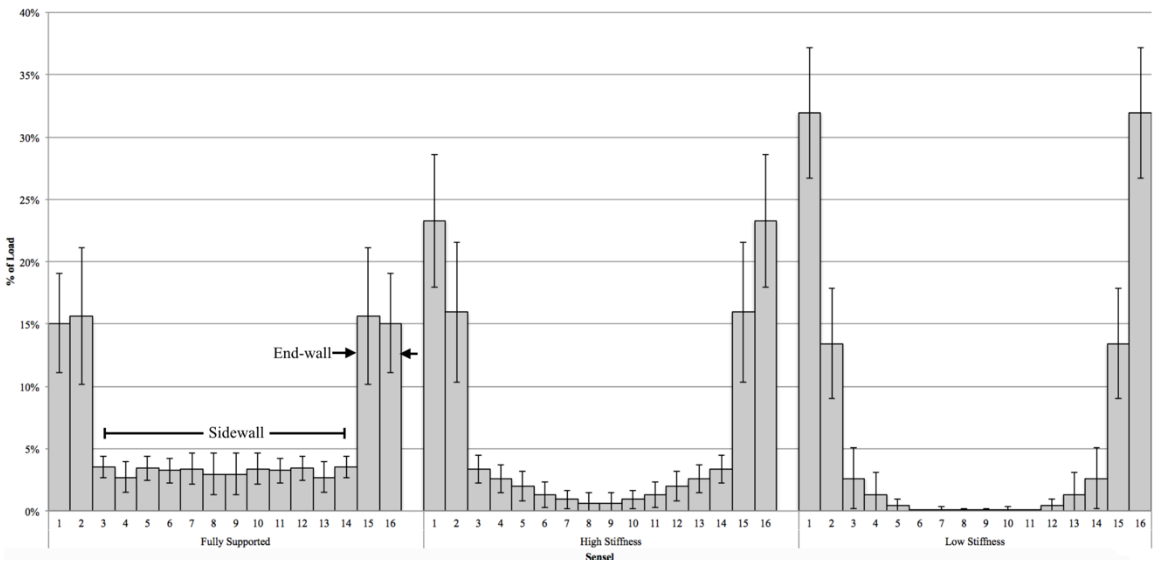

Figure 49 Normalized distribution of stress along the length of a box in three support conditions: fully supported, on High stiffness deckboards, and on Low stiffness deckboards. The height of the grey bars indicate data mean and whiskers indicate standard deviation.

Testing data was then compared to the model predictions. Figure 50 shows the measured stress distribution along with a graphical representation of the model prediction (red line). While the graphic does not show the deviation in test data, it does give some visual indication of areas where the model does or does not follow the mean of the data. The model appears to slightly over-predict the boxes on High stiffness deckboards and under-predict the central portion of boxes on Low-stiffness deckboards.

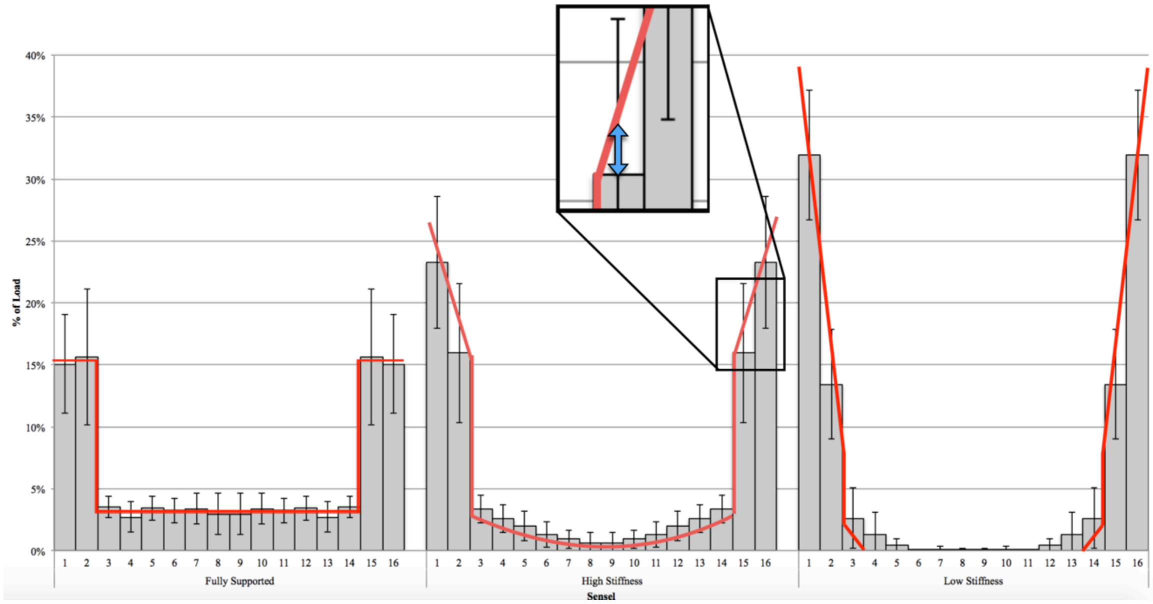

Figure 50 Image of testing data (grey) with graphical overlay of the beam on elastic foundation model (red) for boxes with three support conditions: fully supported, on High stiffness deckboards, and on Low stiffness deckboards. Pop out: The difference (blue arrow) between the data (grey) and model prediction (red) is graphically represented at the center of the sensel.

Euclidean distance is a traditional method of evaluating multiple distributions (in this case each sensel) at the same time. To analyze the true predictive ability of the model, the Euclidian distance was used as a means of determining the residual at all 16 sensel location simultaneously. The Euclidean distance better represents the models' ability to predict the stress distribution across the entire sidewall as opposed to evaluating each point individually. The results are presented in Table 13. The average distance from the true mean to the model is shown as the "Delta Model-Actual", with all values being well within the standard deviation of the actual data. "N tests within Delta" represent the number of tests with a residual less than the "Delta Model-Actual". The "Probability" represents the likelihood of a sample being closer to the true mean than the model prediction. Smaller values indicate good modeling accuracy.

Table 13 Summary of model predictive ability. Delt represents the difference between the model prediction and the actual mean.

Deckboard Treatment	Actual Euclidian Distance	Actual Standard Deviation	CoV (%)	Delta Model-Actual	Test (n)	N tests within Delta	Probability
Rigid Support	0.327	0.104	32.0	0.0141	58	0	1.06%
High Stiffness	0.405	0.115	28.4	0.0261	77	3	1.93%
Low Stiffness	0.491	0.106	21.6	0.0606	134	34	4.26%

In conclusion, the model successfully predicts the distribution of stress across the length of a box at different support conditions and total box loads. The data indicates that the model under-predicts the center sidewall region of boxes on Low stiffness decks. However, the variation between and within boxes is substantial, due in part, to the low resolution of the pressure mat and the inherent variation within boxes.

6.2 Predicting Box Compression Strength at Failure

The box compressive strength was predicted by setting the end-walls to the same stress regardless of support condition. The predicted load on High and Low stiffness deckboard could then be divided by the predicted load at failure on fully supported boxes to produce a failure load ratio (Table 14). The failure ratios were then normalized to the testing data for comparison.

Table 14 Model failure ratio predictions and normalized box failure predictions compared to the tested box failures.

Support condition	Predicted Load at Failure		Measured Load at Failure		
	Ratio	(Normalized) Lbs.	Ratio	Average Lbs.	Standard Deviation Lbs.
Rigid Support	1	413.8	1	413.8	34.8
High Stiffness	0.7425	307.2	0.9154	378.8	21.4
Low Stiffness	0.5395	223.2	0.6885	284.9	30.3

Table 2 shows that the model does a poor job of predicting the failure of the boxes. The difference between measured and predicted is 17.3% and 19.9% for the boxes on the High and Low stiffness deckboards (Table 14). The under-prediction may be due to the previously mentioned under-prediction at the center of the sidewall (Figure 50). However, the center of the sidewall supports a relatively small amount of the total load. Such a large discrepancy prompted further investigation.

The pressure mat data was mined in an attempt to understand the possible source of the discrepancy. First, for each support condition, the maximum pressures at the box corners were not equal as had been assumed. The maximum pressure reading was 67.6 psi for the fully supported boxes while the boxes on High and Low stiffness deckboards produced maximum pressures of 97.0 psi. and 99.6 psi., respectively. While a dramatic loss in stress at the corner correlated with max load on the box, the assumption that the corners would fail at similar stresses, regardless of support condition, was incorrect. This finding partially explains why the tested values were higher than the predicted values. Second, the pressure mat data indicated that the region considered to be the "corner" is substantially smaller in length (1.28 in. on a 10 in sidewall) than previous studies have indicated (3.3 in on a 10 in. sidewall).[17] The unexpectedly high pressure at the corner is likely due to the deckboard deflecting and introducing a horizontal stress component that can be resisted by the length sidewalls and flaps (Figure 51). This finding merits further investigation.

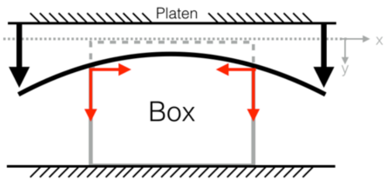

Figure 51 Diagram of box and deckboard under compression with the red arrows indicating the vertical and horizontal forces to the corners.

Third, the model compresses the corners and width sidewall into a one-dimensional "end-wall" represented by only one or two sensels. Therefore, the model does not account for any variation in stress along the end-wall. The pressure mat data indicates that this region may be a source of additional error. Average pressure readings along the end-wall were 13.17 psi when fully supported, 14.6 psi. on High stiffness deckboards and 15.8 psi. on Low stiffness deckboards. Furthermore, the pressure mat data also indicates that the end-wall on the Low stiffness deckboards is supporting more stress at its center than the fully supported end-wall. During testing, it was observed that the High and Low stiffness deckboards twist under load. It is possible that this torsion is actively leveling and optimizing the distribution of forces across the end-wall and therefore generating greater stresses than expected.

The elastic foundation model only evaluates the distribution of vertical forces only along the sidewall. Therefore, any horizontal forces and any variation in the corners or end-walls cannot be modeled. Future studies should consider evaluating these additional variables. Until that time, the beam on elastic foundation model is not a viable means of predicting box compression strength at failure.

7 CONCLUSIONS

Beam on elastic foundation theory was used to generate a model to predict the distribution of forces along the sidewall of a box with beams of differing stiffness.

- The model successfully predicted the distribution of load along the sidewall.
- Modification of beam on elastic foundation theory to account for load bridging and differing stiffness regions was successful.
- The model under-predicted the stress distributed to the sidewall in all but the fully supported scenario.
- For a given load, decreasing the deckboard stiffness increased the stress on the box and more specifically the corners. Decreasing stiffness also increased the variation of measured stresses.

Additionally, the model was rearranged to predict the box compression strength at failure.

- The model was not successful at predicting the compression strength at failure.
- The corners were found to support a much greater load when on High and Low stiffness deckboards.
- The model indirectly accounted for end-wall; therefore, additional variation in stress at this location influenced the predictive accuracy of the model.

- Pressure mat data indicated the high stiffness region at the box corner is much smaller (1.28 in. on a 10 in sidewall) than previous studies have indicated (3.3 in on a 10 in. sidewall). Pressure mat data shows that a critical corner buckling value does not correlate with box failure at this time.

Future studies should consider modeling the horizontal forces being produced at the box corners or evaluate the possibility of variation being induced by twisting deckboards. The model needs further verification with different box sizes, deckboard sizes, and box locations. The model should be modified to account of the asymmetric loading generated by the discrepancy in strength produced by the manufacturers joint. Such a modification may also shed light on the source of box failure. Lastly, it is recommended that a series of tests be run using a pressure mat to quantify the strength of box corners for a variety of box sizes, corrugated flute sizes and paper moisture contents.

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DISSERTATION CONCLUSION

1 SUMARY

In this study a variety of factors that effect box strength were explored. Gaps, flaps, deckboards and locations were all found to have significant effect to varying degrees. Two models were developed during the course of the study. The fist model predicts the loss of strength caused by gaps between deckboards and the second predicted the distribution of stress using the theory of beam-on–elastic foundations.

The findings presented over the four chapters have practical implications of packaging designers. The increase in knowledge has several benefits. First, the improved knowledge around known structural issues such as pallet gaps will allow safety factors to be reduced and replaced with superior designs that do not require unnecessary over packaging. Second, new knowledge was generated for the effect of deckboard stiffness and box gaps, which will allow designers to optimize material usage in their unit load. And finally, the new beam-on-elastic foundation model will not only improve design but help prevent bad designs before they ever reach the market. In every situation the utilization of this information will provide cost, weights, damage and sustainability benefits for companies. A full list of the findings has been included below.

2 CONCLUSIONS

Chapter 1

- Similar reductions in strength were found when boxes were oriented with the width and length sidewall over identical gaps.
- 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 has a similar error to the original equation with both being limited by the inherent variation in corrugated boxes. Error was further reduced by adjusting for moisture content.

Chapter 2

- 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.
- When compared to 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 the gap allowed the deckboards to rotate which altered the direction and magnitude of the forces on the box corners and sidewalls. This effect requires further study.
- 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.

Chapter 3

Compression Strength

- Reduction of box flap length did not have a significant effect on the box compression strength when the flaps were reduced by 25%. This represented a 12% reduction in board area.
- A flap reduction of 50% caused a significant reduction in strength during various tests; however, the reduction was less than 8% in all scenarios except misaligned stacking. Therefore, in a carefully designed unit load it is possible to save 24% in material while sacrificing less than 8% of the box compressive strength.
- Flap reduction has a greater effect on the compression strength of larger boxes.
- The interaction between flap length and deckboard bending indicates that smaller flaps can be used on boxes supported by less stiff deckboards.
- Flap reduction produced a greater strength loss when boxes were in a misaligned in a column stack than when the boxes were in an aligned column stack.

Deformation

- Boxes in all misaligned stack situations had a significantly greater deflection at failure than any of the column stacked situations.
- A 50% reduction in flap length increased the deformation at failure by as much as 16%.

Chapter 4

Beam on elastic foundation theory was used to generate a model to predict the distribution of forces along the sidewall of a box with beams of differing stiffness.

- The model successfully predicted the distribution of load along the sidewall.
- Modification of beam on elastic foundation theory to account for load bridging and differing stiffness regions was successful.
- The model under-predicted the stress distributed to the sidewall in all but the fully supported scenario.
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- The model indirectly accounted for end-wall; therefore, additional variation in stress at this location influenced the predictive accuracy of the model.
- Pressure mat data indicated the high stiffness region at the box corner is much smaller (1.28 in. on a 10 in sidewall) than previous studies have indicated (3.3 in on a 10 in. sidewall). Pressure mat data shows that a critical corner buckling value does not correlate with box failure at this time.

3 PROJECT LIMITATIONS

- The inherent variation in corrugated boxes has limited the predictive ability in all situations.
- Pressure mat testing was limited by sensel resolution.
- The deckboards used in this study were limited due to the lack of PMMA thicknesses available.
- While previous studies have only used one box size the use of two box sizes in this study is still not enough to make general conclusions.
- Lack of linear variable differential transformers (LVDT) inputs limited the assessment of deckboard torsion.

4 RECOMMENDATIONS FOR FUTURE RESEARCH

- Explore additional box sizes on varying gaps.
- Explore additional box sizes on varying deckboard stiffness.
- Explore deckboard torsion.
- Test multiple boxes on low stiffness deckboards to determine if adjacent boxes counteract the deckboard torsion.
- Evaluate multiple box sizes using a pressure mat to quantify size and strength of corners and critical buckling loads of different box components.
- Model full 40in wide three stringers pallets using beam on elastic foundation.
- Quantify deckboard rotational stiffness with differing nails and deckboards.
- Quantify changing corrugated stiffness due to moisture content and the subsequent effect on elastic foundation modeling.