# The Effect of the Stiffness of Unit Load Components on Pallet Deflection and Box Compression Strength

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ABSTRACT (Academic)

Currently, pallets are designed assuming that the load is distributed evenly on the top of the pallet. When pallets are loaded with packages such as corrugated boxes or returnable plastic containers, due to their physical shape, packages, are not capable of deforming freely with the pallet and a bridging phenomenon occurs. During this load bridging phenomenon, a portion of the vertical forces are redistributed as horizontal forces which causes the redistribution of the vertical compression stresses on the pallet towards the support. As a result, the deflection of the pallet can decrease and the load capacity of the pallet can increase significantly. The second chapter of this paper investigates the effect of package content on pallet deflection. The study concluded that package content did not have a significant effect on pallet deflection within the boundary conditions of the experiment.

The third part of this paper considers how a specific pallet characteristic could affect the way a corrugated box performs. Standard box design procedures include adjustments of estimated compression strength for relative humidity, overhang on pallets, vibration, and alignment of boxes. However, there is no adjustment factor for pallet stiffness. The objective of the study described in this thesis is to find an answer for how the compression strength of a box is affected by pallet stiffness and top deckboard twist. The study concluded that the pallet stiffness and top deckboard twist do not have an effect on the compression strength of the box until less than 12% of the area box is supported.

ABSTRACT (General Audience)

Within the United States alone, there are more than 2 billion pallets in service daily. These pallets transport and store a wide variety of products. There are many factors that could effect the performance of a pallet, and it is still unknown which design factors and possible package interactions will or will not effect pallet performance. The first objective of this thesis is to investigate the effect of package content on pallet deflection. The study concludes that the package content does not have an effect on pallet deflection.

With about 1300 manufacturing plants that produce corrugated in the Unites States and Canada, the industry alone provides $26 billion to economies. Corrugated paperboard boxes are used daily for distribution and packaging, allowing products to easily and safely travel the globe. A majority of the time, these boxes are transported and stored on wooden pallets. Currently, there is no safety factor for box design that takes pallet stiffness into consideration. The second objective of this thesis is to investigate the effect of top deckboard twist on box compression strength. The results from the study concluded that the pallet stiffness and top deckboard twist do not have an effect on the compression strength of the box until less than 12% of the area box is supported.

Dedicated to my family who taught me the importance of hard work.

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# Chapter 1: Literature Review

## 1.1 Corrugated Paperboard Boxes

### 1.1.1 Introduction of Corrugated Paperboard Boxes

The purpose of a corrugated paperboard box is to facilitate product storage and distribution and to protect the product as it moves between supplier and customer. In 1871, Albert L. Jones was granted the first patent for a corrugated material that is directly connected to what is known today as corrugated boxes. The patent reads as follows, "The subject of this invention is to provide means for securely package vials and bottles with a single thickness of the packing material between the surface of the article packed…it consists of paper, cardboard…which is corrugated, crimped or bossed…the latter may be made into packing boxes…" [1]. The image of the patent can be seen in Figure 1. Through multiple patents, researchers were improving corrugated material over the years, it was in 1914 when the Pridham Decision allowed a breakthrough for the market of corrugated paperboard boxes. The Interstate Commerce Commission broadened the motor freight and rail carrier specifications to include corrugated paperboard boxes as shipping containers. They also lessened doubts about corrugated paperboard by stating products behaved the same during shipment regardless of being transported in a wooden or corrugated container [1]. However, it was not until 1970 that corrugated containers began to make a significant presence in the shipping industry. A third of corrugated containers were used for food products while another third was used for other consumer products that were non-perishable, such as, soap, paint, textiles, and tobacco. The remaining percentage of corrugated containers were used for heavy industrial products [1].

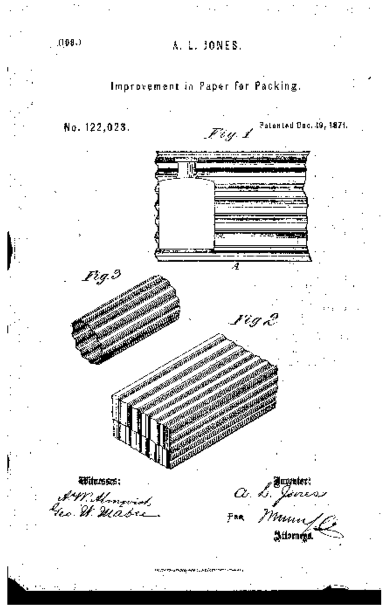


**Figure 1.** US Patent 122,023 of corrugated material granted to Albert L. Jones in 1871 [1].

In the present day, corrugated has become a material the shipping industry has come to rely on. Ninety percent of packaged products use corrugated paper [2]. In 2013, 78.95 million tons of corrugated were produced by United States paperboard mills alone for the purpose of packaging [3]. The use of corrugated boxes includes a large variety of products as food, beverage, consumer electronics, retail displays, etc, while also providing protection as a primary, secondary, or even tertiary package [4].

### 1.1.2. Terminology of Corrugated Paperboard Boxes

In order to understand the design of the corrugated paperboard box, there is a body of specific terminology that must first be understood. The liner is the flat sheet of paperboard fiber. The medium is the corrugated sheet of paperboard that developed into a repeating sinusoidal shape. The image of the liner and medium can be seen in Figure 2. The flute of the corrugated refers to the size and shape of the corrugated paperboard medium. Within the paperboard industry, there are four different types of flute sizes that are typically manufactured, A flute, C flute, B flute, and E flute. A flute if the largest thickness while E flute is the smallest thickness. The thickness of C flute and B flute fall between A and E flute. Figure 3 displays the graphic representation of different flute types.

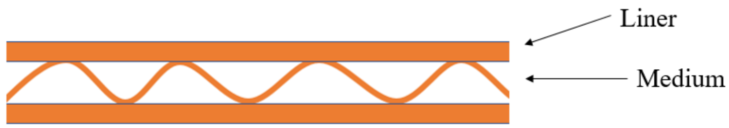


**Figure 2.** Graphic representation of liner and corrugated medium.

The basis weight or grammage of the corrugated components assists in keeping consistent quality among manufactured corrugated. It is the amount of fiber by weight in a given area of the liner and the medium. The difference between basis weight and grammage is the unit of measurement. Basis weight is measured in pounds per thousand square feet while grammage is measured by grams per square meter (TAPPI T410) [5]. It is displayed as the outside liner basis weight/medium basis weight/inside liner basis weight, for example, 33/28/33. Basis weight can be used to conclude that heavier corrugated will perform better than lighter corrugated [1].

The caliper is the combined thickness of the liner and the medium together. The caliper is affected largely by the flute and the number of liners and mediums, and is a significant factor in determining box compression strength [6]. There are also different liner and medium combinations to be aware of, that can be referred to as board style. When there is only one liner and one medium, the corrugated is referred to as single-face. Single-wall is two liners with a medium in between them. Double-wall is three liners and two mediums between them, while triple-wall has four liners and three mediums between them. Figure 3 displays the various combinations of liners and mediums.

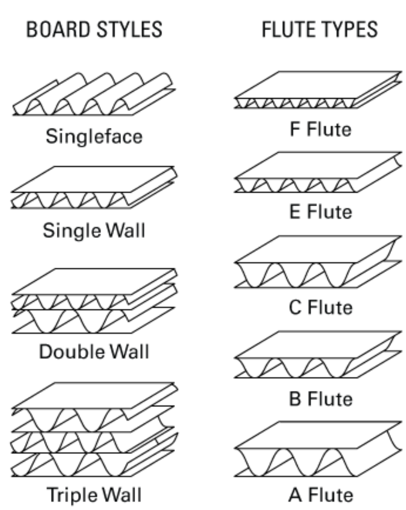


**Figure 3.** Various board styles and flute types of corrugated paperboard [8].

### 1.1.3. Design of Corrugated Paperboard Boxes

There are many box designs. The most common design for shipping is the regular slotted container (RSC) [7]. Aside from slotted containers, there are also telescope designs, one-piece folder designs, bliss style with end flaps, self-erecting six corner trays, and tubes. The above-mentioned designs can be shown in Figure 4. The European Federation of Corrugated Box Manufacturers (FEFCO) develops the name and 4-digit code system for the various styles of corrugated paperboard boxes. Among the FEFCO designs, there are also a large variety of customized corrugated paperboard boxes that are developed for specific product uses throughout multiple industries.

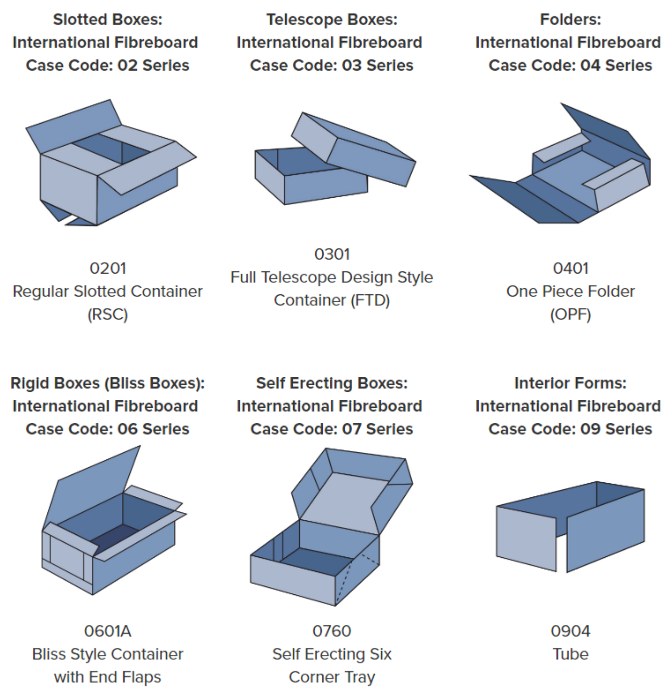


**Figure 4.** Design styles of corrugated boxes [9].

### 1.1.4. Testing Methods of Corrugated Paperboard Boxes

Corrugated paperboard boxes have multiple characteristics to describe and evaluate the strength and potential performance of the box. The Technical Association of the Pulp and Paper Industry (TAPPI) has developed various testing standards and procedures to evaluate the various properties of corrugated paperboard boxes. A few common corrugated tests include, edge crush test, flat crush test, mullen burst test, and the flexural stiffness test.

The edge crush test (ECT) is a widely-used test to measure the compression strength of corrugated paperboard. The value obtained from the ECT is one of the most important values and is believed to have a significant impact on the overall compression strength of a corrugated paperboard box [7]. Though there are many variations of the ECT test, such as the short span compressive strength test (TAPPI T826) [10], ring crush test (TAPPI T822) [11], Concora liner edge crush test (TAPPI 801) [12], and Concora fluted edge crush test (TAPPI T811) [13], the most commonly used method in the industry to obtain ECT values is TAPPI T811 [13]. This test uses rectangular shaped samples where the tested edge is dipped in paraffin wax to prevent unwanted edge damage. A load is then applied parallel to the flutes of the sample until failure. The ECT is largely affected by the caliper of the corrugated paperboard.

The flat crush test (FCT) is described by TAPPI T808 [14]. The FCT is a method of measuring the strength of the corrugated medium by applying a load perpendicular to a circular sample of corrugated paperboard until the flutes of the medium compress. The FCT represents the ability of the corrugated medium to keep its sinusoidal shape, which leads to determining the cushioning ability and durability of the corrugated paperboard. The FCT can be affected by multiple factors such as, thickness, shape, and basis weight of the flutes.

The Mullen burst test is described in in TAPPI 810 [15]. The test uses a hemispherical hydraulic diaphragm to apply pressure to one side of a circular sample of corrugated paperboard until the sample ruptures. The results from this test assist in determining how well the corrugated paperboard will resists damages during transportation.

The flexural stiffness test or bending test (TAPPI 820) [16] measures the flexural stiffness of a corrugated paperboard panel. A rectangular sample that must be at least 1 in. wide and 6 in. long, is placed across a four-point bending machine and a load is applied.

### 1.1.5. Compression Strength of Corrugated Paperboard Boxes

There are many factors that influence the compression strength of corrugated paperboard boxes. Two of the most important factors to consider are the moisture content of the box and the relative humidity of the environment. It should be noted that there is a standard conditioning procedure described in ASTM D4332 [17]. Prior to testing should be conditioned at 73.4±2 °F and 50±2% relative humidity for 72 hours prior to testing. Conditioning each sample for testing is essential for consistency and to reduce test variation [18].

A few manufacturing processes of corrugated paperboard boxes that can affect the compression strength include the sealing method and the flaps of the box. The primary sealing methods of corrugated box flaps is hot melt adhesive and different types of tape. Hot melt adhesive provides secure sealing while tape allows some movement of the flaps allowing rotation [18]. "Boxes with the minor (interior) flaps unrestrained have compression strength test values 6% to 10% higher on average than boxes with the minor flaps attached to the major (outer) flaps [18]."

The two primary standards that are used in the industry to test the compression strength of corrugated paperboard boxes are TAPPI T804 [19] and ASTM D642 [20]. The method of both standards required the corrugated paperboard box to be conditioned and then then placed between two platens of a compression tester. The most common rate at which the top platen movement applies a load towards the box is 0.5 in. per minute. However, before the compression test is performed, a pre-load is applied. The deflection measures begin at the preload level [21]. Once the compression test begins, a load is applied to the corrugated paperboard box until visual deformation, such as buckling or creasing, occurs or a specified load is reached.

Within the platen compression test, there are also different types of platens that can be used, a fixed platen or a floating platen [22]. Since the two platen methods can generate different test results for industry standards, it is important to understand the difference between the two [23]. The fixed platen is stable and does not move during the test, it is used to apply a uniformly distributed load across the top of the box throughout the test. The floating platen is not bolted in place, allowing it to swivel during the test. The movement of the floating platen allows it to distribute the applied load to fail the weakest part of the box first. An example of the load-deflection curve can be seen in Figure 5.

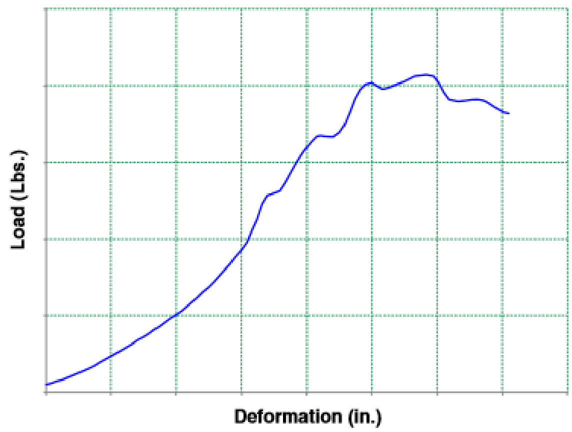


**Figure 5.** Load-deflection curve of corrugated paperboard box [18].

There have been numerous studies performed in the past to investigate different factors that affect the compression strength of a box. In 1963, Kellicut investigated the effect of box content on compression strength. He found that loose content increased the compression strength of a box by 4.5% [24]. It was also found that overhanging a corrugated box on a pallet decreases the compression strength as the amount of overhang increases [25]. There have been multiple studies that have explored the effect of pallet gaps on box compression strength. The results were not consistent. It should be noted a majority of these studies used rigid surfaces as their pallet simulation. A past study performed using a rigid surface resulting in the conclusion that box compression strength decreases as pallet gap increases [25]. However, Ievans found a specific pallet gap (3 in.) had no effect on the box compression strength, but 5 in. and 7 in. gaps reduced that compression strength by 8% and 15% [26]. A later study investigating pallet gaps found larger boxes are affected less by the pallet gaps than small boxes. The location of the gap under the box affects the compression strength as well [27]. Singh investigated how pallets affect the box compression strength and concluded the compression strength of palletized empty corrugated boxes on a block pallet is higher than compression strength of similar stacked boxes on a stringer wood pallet [28]. In another study, it was found that the pallet stiffness does not have an effect on the box compression strength of a box when an approximately 3 in. gap was present [29]. The inconsistent findings between the studies that investigated pallet gaps may be due to interactions between packages and pallets that are currently undergoing investigation. A study of the effect of the aspect ratio (ratio of length to width) concluded that the maximum compression strength of a corrugated box is reached when the aspect ratio is 1.6 [30]. The method of securing the manufacturer's joint of a corrugated box did not have an effect on the box compression strength [31].

## 1.2 Wooden Pallets

### 1.2.1. Introduction of Wooden Pallets

ANSI MH1 defines as a pallet as "portable, horizontal, rigid, composite platform used as base for assembling, storing, stacking, handling, and transporting goods as unit load; often equipped with superstructure; described by providing the following information in the sequence listed: class, use, type, style, bottom deck, size, and design" [32]. It is the most common base for unit loads. It is easily used with mechanical handling equipment within retail stores or complex supply chain systems, allowing faster and easier loading and unloading of goods. Pallets have been used to transport products since World War II [33]. The first pallet patent was published in 1937 by George Raymond and William House of the Lyons Iron Works Company of New York. The two designers state in the patent, that pallets had been in use before their design; however, their design includes easy access for mechanical handling equipment on the short sides of the pallet [34]. Figure 6 displays an image of the patent.

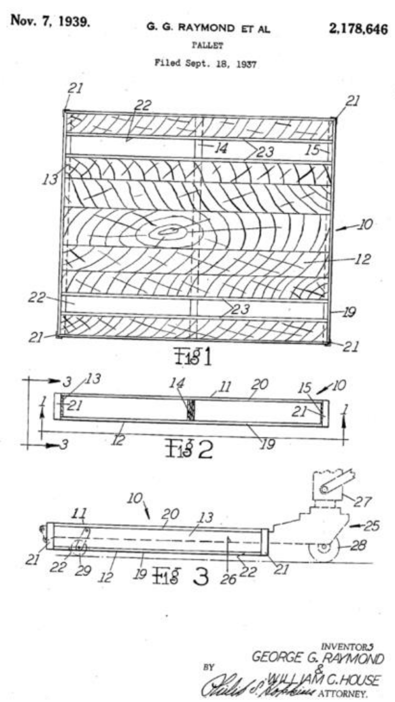


**Figure 6.** Patent of pallet design created by George Raymond and William House in 1937 [34].

Currently, 90% of the pallet market is comprised solely of wooden pallets [35] and within the United States alone, there are more than 2 billion pallets in service daily [36]. Pallets can be manufactured from plastic, composite, metal, and corrugated paper board, and wood. Pallets can be reusable, repairable, and recyclable. In the United States, there are approximately 441 million new wooden pallets manufactured every year [37]. A majority of the time, the price of a pallet is the main decision factor for most companies [38]. This gives wooden pallets an advantage because they not only have high strength, good durability, and a wide range of functionality, but they are typically less expensive. However, wooden pallets also have few disadvantages. They can harbor and transport insects, wood can develop mold, moisture can be given off from damp wood, and fasteners used for construction can damage products that sit on top of the pallet [38]. "The pallet industry recovers a significant amount of its own wood materials, thus playing an important role in efforts to conserve natural resources and reduce the amount of waste sent to landfills [39]."

### 1.2.2. Terminology of Wooden Pallets

In order to understand the characteristics that affect the performance of pallets, one must know the terminology that goes alongside the design process. The two main classes that wooden pallets are distinguished as, stringer class pallet or block class pallet. Depending on the application and the material used, wood pallets can be designed for multiple or single use [7]. Stringer class pallets are the most commonly used type of pallet and have lower manufacturing cost compared to block pallets [40]. The stringer is the component on a pallet that connects the top and bottom deckboards together with its length. They are also the most frequently used pallet in North America and are commonly referred to as the Grocery Manufacturer's Association (GMA) pallet [38]. A block class pallet is generally stronger and more durable than a stringer class pallet [41]. It is widely used within pallet pooling companies, where the pallet is being used for multiple times and for long durations in supply chain. A wooden block class pallet uses nine blocks connected with stringer boards to connect the top and bottom deckboards together. Aside from the block and stringer differences between pallets, there are common terms between the two, such as top deckboard, bottom deckboard, width of pallet, length of pallet and pallet gap (deck spacing). Figure 7 displays a stringer class pallet with its corresponding design aspects labeled. Figure 8 provides a graphic labeling of a block class pallet.

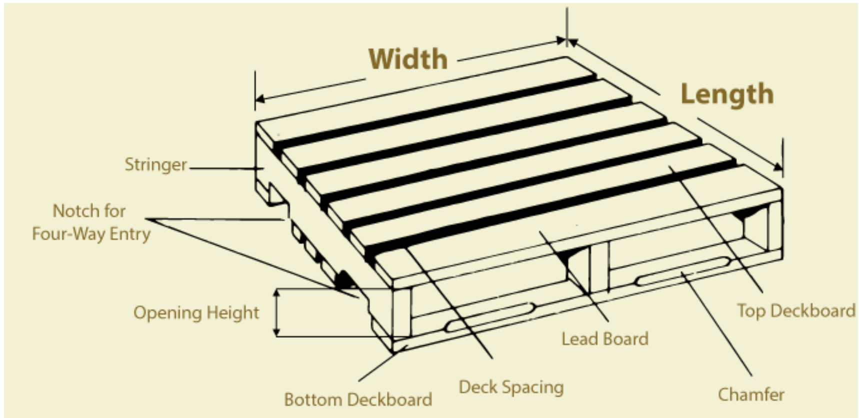


**Figure 7.** Stringer class pallet with labeled components [42].

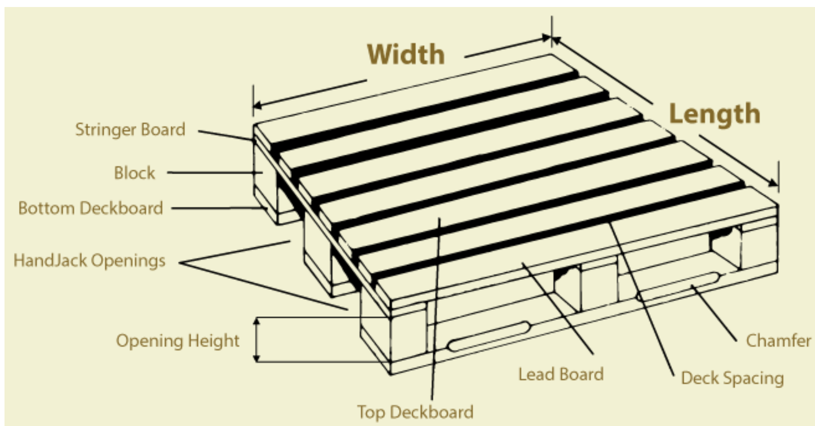


**Figure 8.** Block class pallet with labeled components [42].

Aside from stringer and block classifications, pallet designs are differentiated based on their accessibility by pallet jacks or fork lifts such as, two way, four way, and partial four way. A two-way pallet is accessible by a pallet jack or a fork lift only through the width sides of a pallet. A four-way pallet is accessible by a pallet jack or a fork lift through each width side and each length side of a pallet. A partial four-way pallet is accessible by a forklift through all four sides of a pallet, but only accessible by a pallet jack through the width side of the pallet. An image of the different entry ways can be seen in Figure 9. Typically, stringer class pallets are manufactured as partial four-way and two-way pallets while block pallets are manufactured as four-way pallets.


**Figure 9.** Representation of four way, partial four way, and two way pallets [43].

### 1.2.3. Design of Wooden Pallets

There are various characteristics to consider when designing a pallet. It is important to be aware of the components that can affect pallet performance. For example, the size of the pallet, the material of the pallet, any treatment that the pallet needs to go through for shipping requirements, etc. Even the condition of how the pallet is stored has an effect on the pallet performance.

The size of the pallet is dependent on the industry where the pallet is used, where it is being used geographically, and the application of the pallet. The standard pallet size used in the United States is 48 in. x 40 in. While in Europe, the standard pallet size is 1,200mm x 1,000mm and in Asia, the standard pallet size is 1,100mm x 1,100mm [44]. The grocery industry uses 48 in. x 40 in. pallets, while the beverage industry uses 37 in. x 37 in. pallets and the automotive industry uses 48 in. x 45 in. pallets [37].

Wooden pallets can be manufactured from hardwood and softwood lumber. The pallet industry used over 6.3 billion board feet of wood for pallet manufacturing in 1995 [45]. The wood used in the pallet will depend geographically where the manufacturing plant is located. In the United States, Maple, Birch, and Spruce-Pine-Fir (SPF), are used in the Northeast, while Oak, Yellow-poplar and Southern pine are used in the Southeast and SPF and Red Alder are utilized on the West Coast [32]. The mechanical behavior of a wood pallet is affected by the lumber used in manufacturing. The quality of lumber is variable according the presence of different knots, holes, and splits [46].

Fasteners are the primary method to secure pallet joints together. The American National Standards Institute (ANSI) MH1 (Materials Handling 1) for Pallets, Slip Sheets, and Other Bases for Unit Loads outlines the minimum quality of fasteners that must be used for a single or multi-use pallet [47]. Different fasteners and wood combinations assist in making predictions on pallet joint behavior [47]. The characteristics of the pallet joints have an effect on the structural performance of the pallet when a load is placed on top [48]. Wallin also determined the allowable withdrawal loads for different types of nails within lumber [49].

There are two computer-aided software programs that assist in pallet design. Pallet Design System (PDS®) [50] and Best Pallet™ [51] are both utilized to aid in the design process by predicting the strength of a design and improving the final product for cost efficiency [47]. The design software provides an extensive library of material properties and has built in variation and safety factors.

Pallets are widely used throughout the globe and a special treatment of the pallet may be required when shipping between various countries in order to eliminate the spread of undesired insects. The Food and Agriculture Organization of the United Nations (FAO) issued a treaty established by the International Plant Protection Convention (IPPC) to require any international shipment of wood packaging materials (pallets, crates, boxes) to go through phytosanitary treatment. The treatment is regulated by the International Plant Protection Convention (IPPC). The most common approved phytosanitary treatments are the heat treatment and the methyl bromide treatment [52]. Wood products undergoing heat treatment must be heated to a minimum temperature of 132.8°F for 30 minute while the wood products undergoing the methyl bromide treatment must be fumigated at a minimum temperature of 50°F for 24 hours [53]. If a wooden pallet has undergone any treatment, there will be a stamp placed on the pallet stating which treatment was performed on the pallet, the country of origin, and the company who executed the treatment. An image of the stamp can be seen in Figure 10.


**Figure 10.** Example of heat treatment stamp on a pallet. [54]

Pallets are stored in various support conditions when placed in warehouse areas. It is essential for the general safety of the warehouse to know the exact specifications of the pallet support conditions because they can significantly affect the behavior of the pallet [55]. The different storage conditions of a pallet include floor stacking, fork tine support, and warehouse racking. In a warehouse rack, the pallet can be racked across the length (RAL) or racked across the width (RAW). A floor stacked condition is when the pallet is stored on the floor with all bottom deckboards touching the ground. When a pallet or unit load is floor stacked, usually another pallet or unit load is stacked on top. During material handling, the pallet is often supported under its top deckboards by the fork tine of the forklift. This condition is called fork tine support. Each support condition distributes a stress load differently.

### 1.2.4. Testing Methods of Wooden Pallets

There is a large range of standardized tests for wooden pallets that assist in determining the strength and durability of pallets in various conditions of use. Each test is specific in evaluating a specific component of the pallet. ASTM D1185 [56] and ISO 8611 [57] provide methods for the measurement of the strength and stiffness of the pallet in various warehouse support conditions and evaluating the durability of the pallet using free fall drop, and incline impact tests.

Both standards offer a variety of bending and compression tests to assess how certain storage conditions or loading methods that the pallet would experience during real-life use, would affect its strength and stiffness. For example, there are different pallet bending tests to simulate the following support conditions, floor support, fork tine support, rack support, and conveyor support. There are also different loading conditions that can be chosen such as, uniformly distributed flexible load, uniformly distributed rigid load or even a discrete load provided by the product itself. Aside from bending tests, compression tests on block or stringers can be performed as well to represent the effect of rigid loads. Incline impact tests are run on angled sleighs to simulate pallet durability against fork tine impacts either on the lead deckboard of a pallet or the block of a pallet. Drop tests for pallets are performed to determine the amount of deformation resistance a pallet can have when impacted on the corner or the edge.

There are important methods in each standard that one should be aware of before deciding which method to choose. ASTM D1185 – "Standard Test Methods for Pallets and Related Structures Employed in Materials Handling and Shipping" is mainly accepted in the United States. It does not differentiate tests between nominal and maximum working loads. It also uses a flexible airbag for comparative testing. On the other hand, ISO 8611 is widely accepted internationally and differentiates nominal and maximum working load tests. ISO 8611 utilizes rigid beams for nominal load testing and is the newest pallet testing standard. Similar tests performed for each standard will produce different results, therefore the two standards provide comparative tests.

## 1.3. Unit Loads

### 1.3.1. Introduction of Unit Loads

A unit load is a structure of multiple components (such as pallet, package, and stretch wrap or strapping) that can be transported, stored, and handled as a single unit. In present day, an example of a unit load would be products stacked together on top of a pallet and secured with stretch wrap. Unit loads make handling bulk loads easier and faster whether it is off-loading/loading, transporting or even saving space during storage.

### 1.3.2. Design of Unit loads

The most common base of a unit load is a pallet. Once the pallet is chosen, products are placed on the pallet. Products can be stacked in various ways, such as column stacked, interlocked, or custom and combined patterns. A column stacked pattern is when the products are aligned directly on top of one another. Interlocked is when the products are turned 90-degrees from one layer to the next. One must be cautious when stacking boxes because the stacking strength of the box could decrease if boxes are misaligned [26]. Once products are stacked on a pallet, a load stabilizer is most likely will be added. A load stabilizer could be stretch wrap, strapping, corrugated covers, or possibly slip sheets. Stretch wrap is manufactured in different thicknesses, referred to as gauge. Aside from stretch wrap, there are also stretch hoods and shrink wrap or hoods. Stretch wrap is wrapped around the unit load while shrink wrap is covered loosely around the unit load then tightens and shrinks when heat is applied. A stretch hood is when a tube of film sealed only on one end is stretched tightly over a unit load. However, stretch wrap is the most common plastic film stabilizer because the heat from shrink wrapping could damage products within the unit load and stretch hood machinery has a high cost [58]. The type of unitized load and the method shipping has an affect on what type of wrapping will be placed on the unit load [59]. Besides stretch wrapping, banding or strapping of unit loads can be effectively used to stabilize unit loads. Straps or bands can be made of different types of materials, such as nylon strapping, metal strapping, or polyester strapping. To achieve the optimal unit load stability, a number of straps need to be placed to various locations around the unit load depending on the type of the packages or products transported. Some unit loads may have three straps across the length and two straps across the width of the unit load, or some unit loads may only have two straps across the length of unit load. Edge and corner protectors either created from foam, paperboard, or corrugated may be placed along the top, bottom, or sides of a unit load to assist in decreasing damages during handling. Slip and tack sheets can be placed on the top of a pallet between the first layer of products or between package layers as well. Slip and tack sheets provide friction under the first layer of products which can possibly increase the stabilization of a unit load. Figure 11 displays a graphic representation of a unit load with possible forms for load securement.

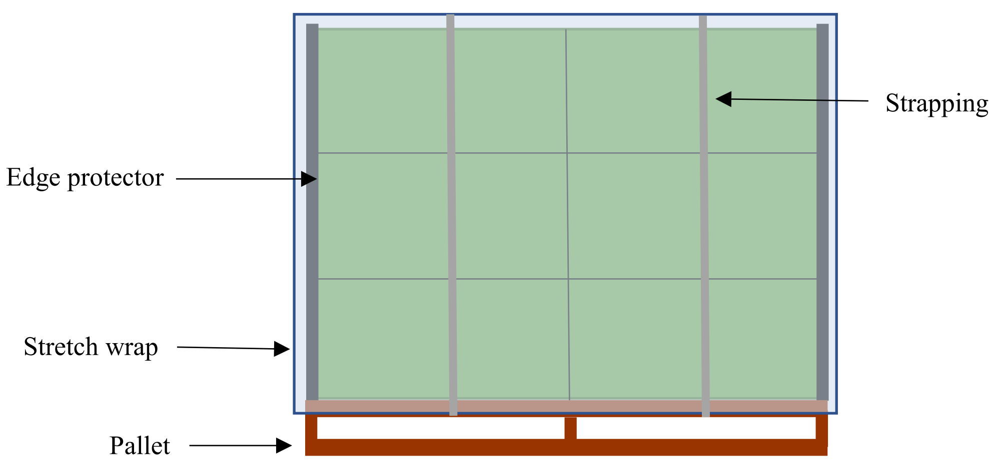


**Figure 11.** Unit load example with labeled stabilizers.

### 1.3.3. Testing Methods of Unit Loads

Similar to pallet testing, unit load testing is comprised of compression, incline impact, and vibration testing with an addition of a forklift handling obstacle. ASTM D4169 [60] Standard Practice for Performance Testing of Shipping Containers and Systems and ASTM D642 [19] Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads both outline methods for completing these tests. Compression tests for unit loads are performed to evaluate the ability of the unit load to resist an applied external compressive force. Compression tests can compare the resistance abilities of different unit load designs. Vibration tests are run on unit loads to simulate the same vibration the unit load would incur from a trailer truck path or an airline flight which can assess unit load stability. There have even been studies to determine how products interact in unit loads when vibrated. Weigel found the product has the large effect on the natural frequency of the unit load, which leads us to believe understanding the behavior of the product during vibration is essential in the unit load design [61]. Incline impact tests can also be performed on unit loads. The unit load will be placed on an angled sled and released to impact a flat back board. The horizontal displacement between products layers after each impact is measured during this test to compare containment methods. A fork lift obstacle can be conducted on a unit load sample to see how the unit load would behave on a simulated warehouse path. During this test, the unit load is transported on a forklift going over one bump and making two turns.

## 1.4. Interaction Between Pallets and Packages

When designing and testing pallets, it is assumed the load on top on the pallet is uniformly distributed. However, this assumption may be unrealistic and could lead to incorrect predictions of how the pallet will perform in terms of deflection and load carrying capacity. This is due to a phenomenon referred to as load-bridging. This describes the bridging that occurs between packages that are placed on top of a pallet. The packages push together horizontally and become stiff, shifting the forces from being completely vertical on the pallet to being redistributed horizontally among the packages. In 1982, the effect of load-bridging on pallet performance was investigated and resulted in the conclusion that when load-bridging is present, the pallet deflects less versus when an applied load is on the pallet [62]. A follow-up investigation determined that ignoring load-bridging may result in conservative pallet designs [55]. Collie also discovered package size, package type and pallet stacking pattern have an impact on load-bridging and pallet performance. Load containment was also found to have effect on load-bridging [63]. Load-bridging was further investigated in 2011 and it was discovered that load-bridging caused forces between the pallet and package to be discreetly distributed which resulted in a negative effect on the pallet and package performance [48, 64]. Since there are so many various components that have the potential to contribute to the effect of load-bridging on pallet and package performance, specific and detailed studies continue to be conducted. Park found increasing package sizes decreases pallet deflection and that moving from B-flute to E-flute corrugated boxes decreased the pallet deflection as well [65].

## 1.5. References

[1] Maltenfort, GG. Corrugated shipping Containers: an engineering approach. Jelmar Publishing Company. 1988.

[2] Twede, D. The History of Corrugated Fiberboard Shipping Containers. 2007: 1–6.

[3] 2014 AF&PA Sustainability Report. American Forest and Paper Association. Washington, D.C. 2014.

[4] Fibre Box Association. Fibre Box Handbook. Fibre Box Association. 2005.

[5] TAPPI T410 Grammage of paper and paperboard. 2013.

[6] McKee, RC., Gander, JW., Wachuta, JR. Compression Strength Formula for Corrugated Boxes. Institute of Paper Chemistry, Appleton, WI. 1963: pp. 149–159.

[7] Twede, D., and Selke EM. Cartons, Crates and Corrugated Board: Handbook of Paper and Wood Packaging Technology. 2005: pp. 155-168.

[8] Sai Packaging Industries. http://www.saipackaging.net/wpcontent/uploads/2016/07/corrugated-flute-types.png. October, 14, 2015.

[9] FEFCO. http://www.fefco.org. October 14, 2015.

[10] TAPPI T826 Short span compression strength of containerboard. 2013.

[11] TAPPI T822 Ring crush of paperboard (rigid support method) 2007.

[12] TAPPI T801 Impact resistance of fiberboard shipping containers. 2002.

[13] TAPPI T811 Edgewise compressive strength of corrugated fiberboard (short column test). 2007.

[14] TAPPI T808 Flat crush of corrugating medium (CMT test). 2006.

[15] TAPPI 810 Bursting strength of corrugated board. 1998.

[16] TAPPI 820 Flexural stiffness of corrugated board. 1985.

[17] ASTM D4332. Practice for Conditioning Paper and Paper Products for Testing. West Conshohocken, PA: ASTM International. 2010. doi:10.1520/D0685

[18] Frank, B. "Corrugated Box Compression—A Literature Survey." Packaging Technology and Science 2014 (27): pp. 105-128.

[19] 5. ASTM D642. Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads. West Conshohocken, PA: ASTM International. 2010.

[20] TAPPI T804 Compression test of fiberboard shipping containers. 1997.

[21] Surber, R. and Caitlin A. "Estimating the effects of interiors on corrugated box stacking strength." Packaging Technology and Science 1982 (28): pp. 15-23.

[22] Maltenfort, GG. Corrugated Shipping Containers: an Engineering Approach. Jelmar Publishing Company, Plainview, NYStone, 1986.

[23] Stone, L. Compression testing: fixed vs. floating platen, paper presented at the 2011 ISTA International Transport Packaging Forum, Orlando FL.

[24] Kellicut, KQ. "Effect of Contents and Load Bearing Surface on Compressive Strength and Stacking Life of Corrugated Containers". TAPPI 1963 (46), pp. 151-154.

[25] Monaghan, J. and Marcondes, J. "Technical Notes: Overhang and Pallet Gap Effects on The Performance of Corrugated Fiberboard Boxes". Transactions of the ASAE 1992 (35.6), pp. 1945-1947.

[26] Ievans, UI. The Effect of Warehouse Mishandling and Stacking Patterns on The Compression Strength of Corrugated Boxes. Tappi 1975 (58): pp. 1–3.

[27] Baker, Matthew, Laszlo Horvath, and Marshall White. "Predicting the Effect of Gaps between Pallet Deckboards on Compression Strength of Corrugated Boxes". Journal of Applied Packaging Research, 2016 (8.3), pp. 30-42.

[28] Singh P., Singh, J., and Saha K. The Effect of Palletized Box Offset on Compression Strength of Unitized and Stacked Empty Corrugated Fiberboard Boxes. Journal of Applied Packaging Research 2011 (5): pp. 157-167.

[29] Baker, Matthew, Laszlo Horvath, and Marshall White. "Effect of Pallet Deckboard Stiffness on Corrugated Box Compression Strength". Packaging Technology and Science, 2016 (29), pp. 263-274.

[30] Zhuan, W., Guangjun, H., and Dejian, Z. Testing Research of Aspect Ratio on Corrugated Box Compression Strength. Applied Mechanies and Materials 2011 (48): pp. 1213-1216.

[31] Singh, J, Bainbridge P, Singh SP, and Olsen, E. Variability in Compression Strength and Deflection of Corrugated Containers as a Function of Positioning, Operators, and Climatic Conditions. Journal of Applied Packaging Research 2007 (2.2): pp. 89.

[32] American National Standards Institute MH1 for Pallets, Slip Sheets, and Other Bases for Unit Loads 2005.

[33] Guzman-Siller, CF. Perception of value of grocery pallet systems: The retailer's point of view. In M.S. Thesis. Michigan State University, East Lansing, MI. 2009.

[34] Patent 2,178,646

[35] Trebilcock, B. "Talking Pallets with Modern Readers". Modern Materials Handling 2013 (68), pp. 23-34.

[36] White, MS, Hamner, P. "Pallets move the world: the case for developing system-based designs for unit loads." Forest Products Journal 2005 (55): pp. 8-16.

[37] Bush, RJ. and Araman, PA. Final Report - Updated Pallet and Container Industry Production and Recycling Research. Virginia Tech, Blacksburg, VA 2008.

[38] Clarke, J. Pallets 101: Industry Overview and Wood, Plastic, Paper, And Metal Options. 2004. Retrieved September 21, 2015.

[39] Bejune, J., Bush R., Araman P., Hansen B., and Cumbo D. "Recycling Behind Most Growth in Pallet Production." Pallet Enterprise 2002: pp. 26-37.

[40] LeBlanc, R., & Richardson, S. Pallets: A North American Perspective. Canada: PACTS Management Inc. 2003.

[41] Brindley, E. Block Pallets in Our Future? Block Pallet Manufacturing Methods. 2008. Retrieved from http://www.palletenterprise.com/articledatabase/view.asp?articleID=2744

[42] Hoffman, M. “All About Different Types of Pallets.” Larson Packaging Company. 2014.

[43] Uline. http://uline.com. January 6, 2016.

[44] ISO 6780: Pallets for Materials Handling – Principal Dimensions for Flat Pallets. 2001.

[45] Reddy, VS, Bush, RJ, Bumgardner MS, Chamberlain JL, and Araman P. Wood use in the U.S. pallet and container industry: 1995. Center for Forest Products Marketing. Virginia Polytechnic Institute and State University, Blacksburg, VA. 1997.

[46] Heebink, TB. Load-Carrying Capacity of Deck Boards for General-Purpose Pallets. USDA Forest Products Laboratories Research Paper 2153, Forest Products Laboratories, Madison WI. 1959.

[47] Loferski JR., Mclain TE, Collie ST. Analysis of racked wood pallets. Wood and Fiber Science 1988 (20): pp. 304-319.

[48] Yoo J. Modeling compressive stress distributions at the interface between a pallet deck and distribution packaging. In Diss. Department of Wood Science and Forest Products. Virginia Tech.: Blacksburg, VA, USA, 2011.

[49] Wallin, WB. Nails Commonly Used in Pallets and How They Relate to Pallet Performance. Northeastern Forest Experiment Station, Forestry Sciences Laboratory, Princeton, WV. 1975.

[50] NWPCA. The Pallet Design System (PDS). Alexandria, VA, USA: National Wood Pallet and Container Association (NWPCA). 1984.

[51] White and Company. Best Load (2011) Blacksburg, VA, USA: White & Company.

[52] ISPM 4. International plant protection convention. 2009-002: Revision 2013.

[53] ISPM 15. International import and export regulations. http://ismp15.com. December 14, 2015.

[54] Boone Valley Forest Products, Inc. http://www.boonevalley.net/tag/heat-treated-dunnage/ January 6, 2016.

[55] Collie S. Laboratory verification of pallet design procedures. In M.S. thesis Department of Wood Science and Forest Products. Virginia Tech: Blacksburg, VA, USA,1984.

[56] ASTM D1185 Standard test methods for pallets and related structures employed in materials handling and shipping. 2009.

[57] ISO 8611 Pallets for materials handling – flat pallets. 2004.

[58] Bisha J. The Effect of Load Stabilizer Selection on Load Shift within Unit Loads. In M.S. thesis Department of Wood Science and Forest Products. Virginia Tech. Blacksburg, VA, USA. 2008.

[59] Singh J., Cernokus E., Saha K., and Roy S. The Effect of Stretch Wrap Prestretch on Unitized Load Containment. Packaging Technology and Science 2014 (27): pp. 944–961.

[60] ASTM D4169. Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads. West Conshohocken, PA: ASTM International. 2009. doi:10.1520/D0642

[61] Weigel, TG. Modeling the Dynamic Interactions Between Wood Pallets and Corrugated Containers During Resonance. In Diss. Department of Wood Science and Forest Products. Virginia Tech: Blacksburg, VA, USA, 2001.

[62] Fagan, B. Load-support Conditions, and Computerized Test Apparatus for Wood Pallets. Department of Wood Science and Forest Products. In M.S. thesis Department of Wood Science and Forest Products. Virginia Tech, Blacksburg, VA. 1982.

[63] White MS., Dibling W., Rupert R., McLeod J. Determination of Pallet Maximum Working Loads from Nominal Load Measurements. Center for Unit Load Design, Virginia Tech, Blacksburg, VA, USA. 1999.

[64] Yoo, J. "Quantitative Analysis of The Compressive Stress Distributions Across Pallet Decks Supporting Packaging in Simulated Warehouse Storage". In M.S. thesis Department of Wood Science and Forest Products. Virginia Tech, Blacksburg, VA, USA. 2008.

[65] Park, J, Horvath, L, White, MS, Phanthanousy, S, Araman, P, and Bush, RJ. The Influence of Package Size and Flute Type of Corrugated Boxes on Load Bridging in Unit Loads. Packaging Technology and Science 2017 (30): pp. 33–43. doi: 10.1002/pts.2279.

# Chapter 2: The Influence of Package Content on Pallet Deflection

## 2.1. Abstract

Within the United States alone, there are more than 2 billion pallets in circulation. These pallets are essential components used to efficiently transport and store goods among warehouses and retail stores on a daily basis. The process of the design and development of these pallets has progressed significantly over the years. However, they are typically designed with the assumption that the weight of unit loads will be uniformly distributed on the pallet surface. When pallets are loaded with various types of packages, they tend to bridge between each other. This load bridging phenomena can affect the deflection of the pallet which could potentially influence its load carrying capacity. The purpose of this study is to investigate the effect of three different simulated package contents on the deflection of a simulated pallet. The experimental results confirm that package size has an impact on pallet deflection. Package size had the most effect on a low stiffness pallet and less of an effect on a high stiffness pallet. The average percent reduction of pallet deflection between small and medium boxes was 19% and between medium and large boxes was 29%. Package content (rigid, semi-rigid, and flexible) was not found to have a significant impact on pallet deflection. The stiffness of the corrugated box alone in this investigation was strong enough to withstand the forces present during the experiment without any extra stiffness contribution of internal reinforcements of the box.

## 2.2. Introduction

Every object that can be seen in a home, from kitchen appliances to living room flooring have been transported, stored, handled, or even sold on a pallet. In the United States alone, there are approximately 2 billion pallets in circulation [1]. Of those 2 billion pallets, 90-95% are manufactured from wood [2]. According to the United States Census Bureau, under the NAICS code (32191) for wood container and pallet manufacturing, \$4.3 billion was spent on the production of wooden pallets and containers in 2014 [3]. Wooden pallets are currently designed to support a flexible load simulated by an airbag (ASTM D1185); however, in the real-world distribution, pallets carry a wide variety of packages (e.g., corrugated boxes, plastic pails, bottles, bags, etc.). Due to their discrete shape, these packages can interact with each other and with the pallet. The effect of this interaction on the strength of products and packaging systems has been investigated by numerous researchers [4,5,6,7,8,9,10,11,12,13,14,15]. Most studies focused on the compression strength of corrugated boxes as a function of stacking patterns [5], pallet gaps [6], pallet stiffness [7], and palletized box offsets [8, 9]. However, the effect of the products on the load capacity of the pallet was only investigated by Park [16].

There are only a few studies that have investigated load-bridging and pallet deflection. In 1982, Fagan [17] investigated the impact of load bridging of a unit load on pallet deflection and discovered when the size of the boxes increased, the deflection of the pallet decreased. Fagan also found that the effect of load bridging was more prominent for low pallet stiffness [17]. In 1984, Collie [18] found that stack conditions have a significant impact on unit load deflection. He concluded that deflection predictions of certain stack conditions must be considered in the pallet design process in order to prevent overestimation of deflection.

Further studies have been conducted to explore the detailed characteristics involved with load bridging of unit loads including the investigation of stress distribution of packages across pallet decks by Yoo in 2008 [19]. The investigation resulted in the conclusion that the stress distribution between packages and pallet decks is non-uniform. Yoo later discovered that stiffer pallets produce lower compressive stresses on packaging than lower stiffness pallets [20].

While load-bridging has been acknowledged in previous studies and there are publications explaining the phenomenon, it is still far from being fully understood. There are multiple variables within a unit load that must be studied in order to discover what has an effect on load-bridging performance and what does not. Research by Park et al. [16] showed that the package size and flute of the corrugated board have an effect on pallet deflection. Yoo [19] found that the stress distribution on the top of the pallet increases when the package stiffness increases. Both studies investigated variables that have an effect on the load redistribution of a pallet that can be related to the phenomenon of load bridging. However, there has been no historical data on the effect of the package content on the pallet deflection. Understanding the effect of package content on the deflection of the pallet is necessary to allow the improvement of the universal pallet design method that incorporates the effect of corrugated boxes. This new method will contribute to the knowledge that could enable members in the pallet and packaging world to design pallets for special applications which will increase the sustainability of pallets by reducing the weight and the amount of wood utilized.

## 2.3. Objectives

The main objective of the project is to investigate the effect of three different simulated package contents on the deflection of a simulated pallet.

## 2.4. Boundary Conditions

The investigation was limited to the following conditions due to the complexity of the numerous variables present:

- A simplified 2-D analysis of the horizontal compression interaction between the packages in column stacking and the vertical compression interaction between the packages and simulated pallet
- The effect of deckboard gaps was not investigated
- Only column stacking was simulated
- No stretch film was present providing an unrestrained load
- Deflection measurement was the sole dependent variable of the analysis
- Box corners are supported throughout testing
- Free-span rack system

## 2.5. Materials and Methods

### 2.5.1. Materials

#### 2.5.1.1. Pallet Segments

In previous research [16], four pallets that are commonly used in the industry were tested using a three-point bending test to measure their stiffness according to ASTM D143 (2000). The exact parameters of the test setup were published in the dissertation of Park (2015) [16]. The samples were supported using two roller supports positioned by leaving a 36in. free span. A universal testing machine (MTS Model 826.75) with a 5000-pound load cell was used for the test. The load deflection curve from the deflection test was used to calculate the pallet stiffness. The measured stiffness of the pallets (Table 1) was adjusted by multiplying the measured stiffness by the ratio of the pallet length and 10 in. to represent a stiffness of a 40 in. x 10 in. segment of the pallet (Table 2). The adjusted stiffness results were used to find plywood and solid spruce-pine-fir (SPF) wood panels that could simulate a common stiffness range for pallets. The plywood panels were tested in the same three-point bending test as the full pallets according to ASTM D143 (2000). The panels were cut to 40 in. x 10 in., where the 40 in. direction was aligned parallel to the grain direction of the outermost veneer layer. The panels were conditioned to room temperature and coated with an outdoor grade stain. The outdoor grade stain was used to prevent moisture absorption by the wood panel. These plywood and solid SPF wood panels will be referred to as pallet segments in the later part of the document. The adjusted stiffness was obtained from testing methods performed from a previous study [16].

**Table 1**. Summary table of the adjusted average stiffness values of commonly used pallets. [16]

| Tested Pallet | Pallet Dimensions (in.) | Adjusted Stiffness (lb./in.) |
|---|---|---|
| Pool Wood Pallet | 48 x 40 | 701 |
| Multiple-use Plastic Pallet | 48 x 40 | 377 |
| GMA Style Wood Pallet | 48 x 40 | 264 |
| Single-use Plastic Pallet | 44.5 x 38.5 | 81 |

**Table 2.** Summary table of the stiffness values of 40 in. x 10 in. pallet segment by material.

| | Tested Specimen | Stiffness (lb./in.) |
|---|---|---|
| **Pallet Segment** | 0.75 in. Spruce-Pine-Fir Solid Wood | 502 |
| | 0.75 in. Birch Plywood | 293 |
| | 0.5 in. Birch Plywood | 93 |

2.5.1.2. Corrugated Boxes

Regular Slotted Container (RSC) type boxes manufactured from nominal 32 lb./in. Edge Crush Test (ECT) value B-flute corrugated board with a nominal board grade of 38/26/38 lb./ft$^2$. were supplied by Packaging Corporation of America (PCA) [21]. The boxes were shipped flat and were erected using a custom jig to ensure that each of the edges had a 90° angle. Boxes with three different outside length, width, and height dimensions were used: 5 in. x 10 in. x 10 in. (Small), 10 in. x 10 in. x 10 in. (Medium) and 20 in. x 10 in. x 10 in. (Large). Each size of box was filled with three types of fillers: rigid, semi-rigid, and flexible. The three fillers were selected to represent the extreme conditions of various products. The rigid filler may represent, for example a computer product with stiff foam placed around it or rigid objects such as canned products. The flexible filler represents products that have headspace and do not touch the sidewalls of the corrugated box, such as some bottle products. The semi-rigid filler represents a granulated product. The different fillers are described in the following paragraph and their graphic representations can be seen in Figure 12.

Oriented strand board (OSB) boxes manufactured using 0.5 in. thick OSB board to the exact inside dimensions of the corrugated paperboard box were placed inside of the corrugated box to simulate rigid filler. The OSB boxes were filled with sand and a lid was secured to the top to seal the OSB box. A semi-rigid filler was simulated with a 0.5 in. thick OSB board with chamfered edges loaded with metal weight secured to the center of the board. A flexible filler was simulated with Nation's Choice® [22] Premium wood pellets inside the box. All boxes, regardless of inside filler, were constructed to a standardized unit load weight of 1,440 lbs as presented in Table 3. Each box flap was sealed with hot melt glue and once assembled, conditioned at 73 °F and 50% relative humidity for at least 72 hours according to ASTM D 4332 (2006).

**Table 3.** Total number of corrugated paperboard boxes and sample weights utilized.

| | **Small** | **Medium** | **Large** |
|---|---|---|---|
| **B-flute** | 144 boxes | 72 boxes | 36 boxes |
| **Weight per box (lbs.)** | 10 | 20 | 40 |

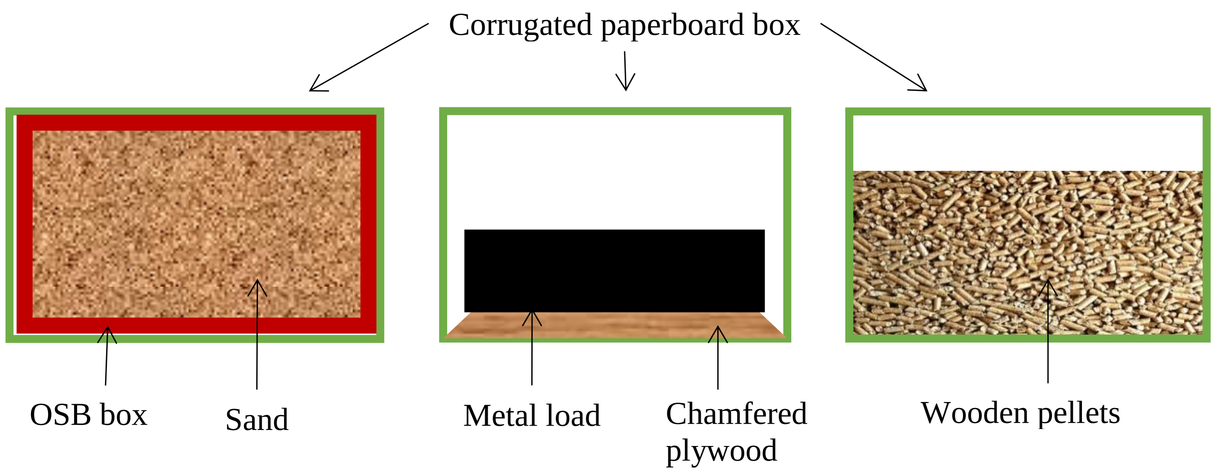


**Figure 12.** Different inside fillers of corrugated paperboard boxes used to simulate the three rigidity levels: Rigid, Flexible, Semi-Rigid.

2.5.2. Methods

**Bending Test of Simulated Pallets using Loaded Corrugated Paperboard Boxes**

A 40 in. x 10 in. simulated pallet segment was placed across two 4 in. wide by 6 in. tall I-beams having a 36-in. free span. Each pallet segment had three screws on the 40 in. edges in order to support the wooden yokes and one to hold the Linear Variable Differential Transformer (LVDT) (Model: 200HR-DC) used for the deflection measurement (Figure 13). A floor jack and dial gauge was placed under the simulated pallet segment to ensure that it was level prior to the measurement. In addition, the jack allowed the boxes to be fully stacked on the pallet segment before applying the load of the boxes to create deflection. This is what enables the load bridging effect to be created. Then three layers of boxes were placed on top of the pallet segment. The Large size boxes had two boxes on each layer, the Medium size boxes had four boxes on each layer, and the Small size boxes had eight boxes on each layer. During the experiment, the floor jack was released and the deflection of the pallet segments was recorded using LVDTs and a computerized data collection system. The experiment was conducted inside of the environmental chamber to maintain a temperature of 73° F and 50% relative humidity for all tests performed according to D4332 (2006).

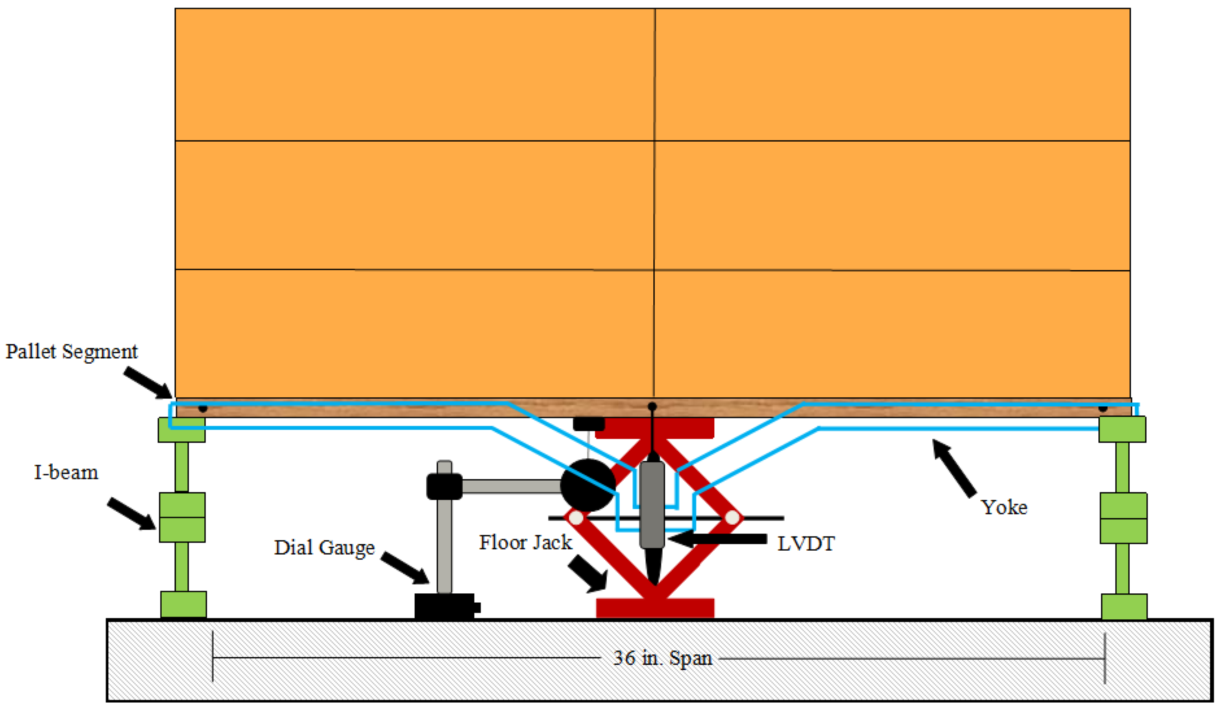


**Figure 13.** Testing set-up of the effect of package content on load bridging.

## 2.6. Experimental Design

The experimental design shown in Table 4 was used to measure the effect of packaging stiffness on the deflection of the pallet. The packaging stiffness was investigated by testing three different inside box fillers; rigid, semi-rigid, and flexible. The independent variables included packaging size, package stiffness, and pallet stiffness. Each independent variable had three different treatments. The dependent variable was the change in pallet deflection. There were three series of tests. Within each series, three tests were run for each combination of pallet stiffness and box support treatment with a new set of corrugated boxes.

**Table 4.** Experimental design to investigate the effect of package content on load bridging.

| Box Size (L x W x H in.) | Support | Low Stiffness Replicates | Medium Stiffness Replicates | High Stiffness Replicates |
|---|---|---|---|---|
| Small (5 x 10 x 10) | Rigid | 9 | 9 | 9 |
| | Semi-Rigid | 9 | 9 | 9 |
| | Flexible | 9 | 9 | 9 |
| Medium (10 x 10 x 10) | Rigid | 9 | 9 | 9 |
| | Semi-Rigid | 9 | 9 | 9 |
| | Flexible | 9 | 9 | 9 |
| Large (20 x 10 x 10) | Rigid | 9 | 9 | 9 |
| | Semi-Rigid | 9 | 9 | 9 |
| | Flexible | 9 | 9 | 9 |

## 2.7. Statistical Analysis

A one-way Analysis of Variance (ANOVA) test at an alpha significance level of 0.05 was performed on each test sample combination to analyze the effects of rigid, semi-rigid and flexible supports on pallet deflection. Assumption tests, such as normality, homogeneity of variances, and independence of observations were completed to ensure the ANOVA test was the proper statistical analysis to perform. ANOVA was also chosen because there was one continuous response and multiple categorical predictors, which falls into the ANOVA model. The statistics software, SAS JMP Pro 12® [23], was utilized to conduct the statistical analysis. The statistical model of the experimental design is shown in Equation 1.

*Equation 1:* $y_{ijkr} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkr}$

Where:

$y_{ijkr}$ = pallet deflection, $\mu$ = overall mean, $\alpha_i$ = effect of $i^{th}$ level of pallet stiffness, $\beta_j$ = effect of $j^{th}$ level of package size, $\gamma_k$ = effect of $k^{th}$ level of package content, $(\alpha\beta)_{ij}$ = joint effect of $i^{th}$ level of pallet stiffness and $j^{th}$ level of package size, $(\alpha\gamma)_{ik}$ = joint effect of $i^{th}$ level of pallet stiffness and $k^{th}$ level of package content, $(\beta\gamma)_{jk}$ = joint effect of $j^{th}$ level of package size and $k^{th}$ level of package content, $(\alpha\beta\gamma)_{ijk}$ = joint effects of $i^{th}$ level of pallet stiffness, $j^{th}$ level of package size, and $k^{th}$ level of package content, and $\varepsilon_{ijkr}$ = random error of all groups.

## 2.8. Results and Discussion

The three independent trials using new corrugated boxes conducted during the experiment did not have a statistically significant difference between them according to a one-way ANOVA test at an alpha level of 0.05; therefore, the results of the trials were merged and handled together throughout the analysis. The average results of the experiment are presented in Table 5.

**Table 5.** Average simulated pallet deflections based on box size and package content.

| Box Size | Package Content | Pallet Stiffness | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Low** | | **Medium** | | **High** | |
| | | Average Deflection (in.) | Tukey's HSD[1] | Average Deflection (in.) | Tukey's HSD[1] | Average Deflection (in.) | Tukey's HSD[1] |
| Small | Rigid | 0.68 (0.01) | A | 0.42 (0.08) | C | 0.19 (0.02) | G |
| | Semi-Rigid | 0.66 (0.02) | A | 0.44 (0.03) | C | 0.167 (0.05) | G |
| | Flexible | 0.67 (0.01) | A | 0.39 (0.01) | C | 0.19 (0.00) | G |
| Medium | Rigid | 0.56 (0.01) | B | 0.31 (0.05) | E | 0.15 (0.00) | H |
| | Semi-Rigid | 0.56 (0.02) | B | 0.32 (0.01) | E | 0.13 (0.05) | H |
| | Flexible | 0.57 (0.01) | B | 0.29 (0.01) | E | 0.15 (0.00) | H |
| Large | Rigid | 0.39 (0.03) | D | 0.21 (0.04) | F | 0.11 (0.03) | J |
| | Semi-Rigid | 0.39 (0.03) | D | 0.21 (0.01) | F | 0.09 (0.05) | J |
| | Flexible | 0.40 (0.01) | D | 0.20 (0.01) | F | 0.13 (0.00) | J |

Note: Numbers in parenthesis are standard deviation values.
[1]Results not connected by the same letter were significantly different based on Tukey's HSD at an alpha level of 0.05.

The effect of box size on the deflection of the pallet segment as a function of the pallet stiffness is displayed in Figure 14. It can be seen that when box size changes from small to medium to large, the deflection of the pallet decreases. The significance of the changes was evaluated using an ANOVA model with a Tukey HSD post-hoc analysis (Table 5) which demonstrated that the change caused by the increasing box size is significant. The same trend was also found by Park and Fagan [16] [17].

Meanwhile, when the effect of package content was investigated on the deflection of the pallet segment no significant differences were found (Table 5).

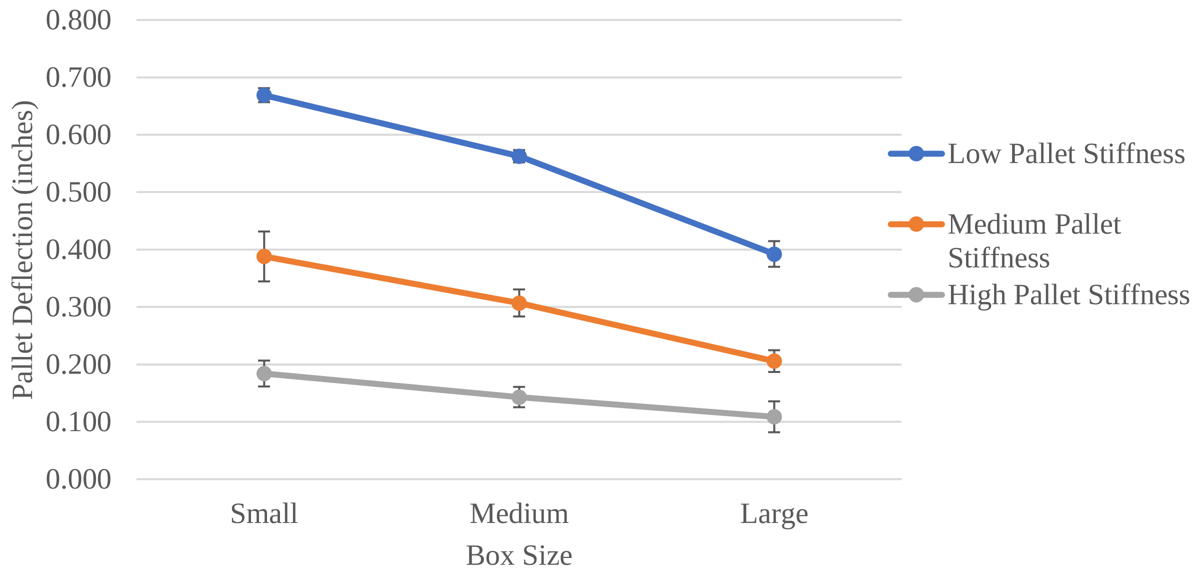


**Figure 14.** Average deflection plot for box size and pallet stiffness.

## Movement of Corrugated Boxes during Pallet Deflection

To further understand the lack of effect of the box content on the deflection of the pallet the movement of the boxes was investigated during the testing. The results are presented in Figures 15 and 16. Regardless of contents, as the pallet segment deflects, the large corrugated boxes tilt and slide away from each other at the base, which creates a triangle-shaped unfilled area between the two columns (Figure 15). The top edges of the top row of the large corrugated boxes touch, but the top edges of the middle and bottom rows do not. For the medium and small corrugated boxes, the boxes stay in the same vertical orientation but shift downward, with the middle columns shifting downward more than the outer columns (Figure 16). The observed phenomena indicate a fundamental difference between the way different sizes of corrugated boxes bridge during pallet bending, independent of contents. This finding indicates that load bridging cannot be generalized and the mechanism causing the boxes to bridge needs to be independently investigated for multiple sizes of boxes. However, within each box size, the movement of the boxes was the same across all package contents indicating the fundamental behavior of the boxes is independent of the box content. It should be noted the headspace was not controlled among the different package contents.

**Figure 15.** Image of large corrugated boxes with rigid fill during deflection.

**Figure 16.** Image of medium and small corrugated boxes with rigid fill during deflection

## Horizontal Pressure between Columns of Large Boxes

The horizontal pressure between the columns of the large boxes was explored further using a TekScan iScan® [17] pressure mat system equipped with Model Number 5400N pressure mat. The pressure mat was placed in between the middle of the columns to measure the horizontal pressure between the corrugated boxes during deflection. The set-up can be seen in Figure 17. To simulate the worst-case scenario when the horizontal pressure is the greatest, the large boxes were filled to maximum capacity with 80 lbs each.

The obtained results were compared to the measured flat crush test (FCT) (measured using TAPPI T809 (2006) of the corrugated board to understand the level of compression that the corrugated boxes experienced when the tops of large boxes touched each other. The results are presented in Table 6. This supports the theory that under the simulated loading conditions the investigated corrugated boxes were stiff enough that the horizontal compression forces did not cause any major deformation; therefore, the extra internal reinforcement of the box due to the different contents could not have an effect on the behavior of the system.

**Figure 17.** Testing set-up to record pressure between boxes with 80 lb of fill.

**Table 6.** Pressure Comparison between Experiment Results and Flat crush test results.

| Pallet Stiffness | Horizontal Pressure using 40 lbs rigid filler (PSI) | Horizontal Pressure using 80 lbs rigid filler (PSI) | FCT Results (PSI) |
|---|---|---|---|
| High | 29.3 | 36.5 | 42.8 |
| Medium | 25.3 | 34.0 | 43.2 |
| Low | 23.2 | 30.9 | 44.3 |

The relationship of the generated horizontal forces to the static frictional reaction forces was investigated with the large boxes. The large boxes were used for this test because they showed the most pallet deflection and movement during testing. The large boxes were each loaded with 80 lbs. to utilize the maximum weight allowed for this box and to simulate the worst-case scenario of shipping. From Table 6, it can be seen that the pressure recorded for the 80 lb boxes was lower than the FCT with the 40 lb boxes measuring an even lower pressure than the 80 lb boxes.

## 2.9. Conclusions

From this experiment, the following conclusions have been made within the boundary conditions:

(1) Package content does not have a significant effect on pallet deflection. There were no significant differences between the performance of rigid, semi-rigid, and flexible package content in regards to pallet deflection.

(2) Pallet deflection is impacted by the size of the package design, supported by Park [16]. Increasing the package size decreased the amount of pallet deflection. Package size had the most effect on a low stiffness pallet segment and less of an effect on a high stiffness pallet segment. The average percent reduction of pallet deflection from small to medium boxes was 19% and from medium to large boxes was 29%.

(3) The behavior of the different size corrugated boxes showed a distinctive difference during pallet bending which indicates that there is a fundamental difference between the interaction of different size packages and the pallet.

## 2.10. References

[1] Trebilcock, B. "Talking Pallets with Modern Readers". *Modern Materials Handling* 2013 (68), pp. 23-34.

[2] "Environmental Benefits of Wood Use for Pallets." 2017. Web access. 13 Sept. 2015.

[3] Bureau, US. "Census.Gov". *Census.gov*. 2016. Web access: 6 Oct. 2016.

[4] Twede, Diana et al. *Cartons, Crates, and Corrugated Board*. 1st ed. Lancaster, PA: DESTech Publications, Inc., 2004.

[5] Ievans, UI. "Effect of Warehouse Mishandling and Stacking Patterns on Compression Strength of Corrugated Boxes". *TAPPI* 1975 (58.8), pp. 108-111.

[6] Monaghan, J. and Marcondes, J. "Technical Notes: Overhang and Pallet Gap Effects on The Performance of Corrugated Fiberboard Boxes". *Transactions of the ASAE* 1992 (35.6), pp. 1945-1947.

[7] Baker, Matthew, Laszlo Horvath, and Marshall White. "Effect of Pallet Deckboard Stiffness on Corrugated Box Compression Strength". *Packaging Technology and Science*, 2016 (29), pp. 263-274.

[8] Singh, SP, Singh J, and Saha K. "Effect Of Palletized Box Offset On Compression Strength Of Unitized And Stacked Empty Corrugated Fiberboard Boxes". *Journal of Applied Packaging Research* 2011 (5.3), pp. 157-167.

[9] Singh, SP et al. "Effect of Lateral Box Offset and Pallet Overhang on Compression Strength of Stacked Fiberboard Boxes and Impact on Stability". *Journal of Applied Packaging Research* 2012 (6.3), pp.129-148.

[10] Weigel, Timothy. "Modeling the Dynamic Interactions Between Wood Pallets and Corrugated Containers During Resonance." *In Diss. Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA Virginia Tech, 2001.

[11] Coles, Richard and Mark J Kirwan. *Food and Beverage Packaging Technology*. Chichester: Wiley-Blackwell, 2011 (1).

[12] White, MS. "The Effect Of Pallet Deck Design On Package Compression." 2015.

[13] Loferski, J. "A Reliability Based Design Procedure for Wood Pallets (Computer Aided, Structure, Methodology)." *In Diss. Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA. 1985.

[14] Heebink, TB. "Load-Carrying Capacity of Deckboards For General Purpose Pallets". *United States Department of Agriculture Forest Service*, 1959.

[15] Kellicut, KQ. "Effect of Contents and Load Bearing Surface on Compressive Strength and Stacking Life of Corrugated Containers". *TAPPI* 1963 (46), pp. 151-154.

[16] Park, J. "Investigation of Fundamental Relationships to Improve the Sustainability of Unit Loads." *In Diss. Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA. 2015.

[17] Fagan, GB. "Load-Support Conditions and Computerized Test Apparatus for Wood Pallets." *In M.S. thesis Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA. 1982.

[18] Collie, ST. "Laboratory Verification of Pallet Design Procedures". *In M.S. thesis Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA. 1984.

[19] Yoo, J. "Quantitative Analysis of The Compressive Stress Distributions Across Pallet Decks Supporting Packaging in Simulated Warehouse Storage". *In M.S. thesis Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA. 2008.

[20] Yoo, Ji. "Modeling Compressive Stress Distributions at The Interface Between a Pallet Deck and Distribution Packaging*". In Diss. Department of Wood Science and Forest Products*. Virginia Tech, Blacksburg, VA, USA, 2011.

[21] Packaging Corporation of America®. Roanoke, VA, USA.

[22] Nation's Choice® Pellets.

[23] SAS JMP Pro 12®. 1989.

# Chapter 3: The Influence of Top Deckboard Rotation on Corrugated Box Compression Strength

## 3.1. Abstract

Corrugated has become a material the shipping industry has come to rely on with 90% of packaged products utilizing corrugated paperboard. The majority of the time, these corrugated packages are stored, transported, and handled on pallets in the form of a unit load. Unit loads distribute weight across the pallet and cause a certain amount of deflection on the top deckboard depending on the deckboard stiffness. It was also discovered in a previous study that the deckboards not only bend, but may also rotate. The strength of corrugated paperboard boxes are also sensitive to changes in support conditions. The objective of this study was to evaluate the combined effect of pallet deckboard deflection and twist on the compression strength of corrugated boxes. The study lead to the following conclusions: pallet top deckboard stiffness does not have a statistically significant effect on the compression strength of the corrugated box when pallet deckboard gaps are present, the percent of supported length of the sidewall and the consequent twist angle only has a significant effect on the box compression strength when 23% and 12% of the length of the sidewall is supported, a linear correlation between the twist and the compression strength of the box was not found, and the gap between pallet deckboards only has an adverse effect if less than 12% of the sidewall length is unsupported. The study also found that there was no significant difference in box compression strength between having an offset present and not having an offset present on top of the pallet segments.

## 3.2. Introduction

With about 1300 manufacturing plants that produce corrugated in the United States and Canada, the industry provides $26 billion to their economies [2]. Corrugated packaging has been used for over a century, with the first patents tracing back to the 1870s [3]. Corrugated paperboard boxes have been used daily for distribution and packaging, allowing products to easily and safely travel the globe. A majority of the time, these boxes are transported and stored on wooden pallets. The boxes are stacked on the top of each other to form multiple layers and stretched wrapped to create a stable unit load. In this unitized form, the bottom corrugated boxes are expected to endure high compressive load; thus, the stacking strength of the corrugated boxes is one of the most important characteristics to consider during their design. Design characteristics of corrugated boxes are calculated using safety factors based on physical and environmental factors such as relative humidity, storage time, severity of handling, vibration, overhang on pallet, pallet gaps, and the alignment of boxes.

There have been various studies that have investigated the many factors that affect box compression. In the 1950s, Maltenfort explored the effect of moisture content on box compression strength, while Kellicut discovered the effect of box content and alignment on box compression strength [4]. In the 1960s, Mckee developed a model that allowed researchers to estimate the box compression strength with the use of edge crush values along with box perimeter and calliper [5]. With the progression of studies done on corrugated characteristics, researchers began to manipulate box design and box assembly to determine any effect on box compression strength. For example, Kutt and Mithel investigated whether to include box flaps and Maltenfort studied the effect of box closure methods [6][7].

Though there have been numerous studies done on corrugated material, corrugated boxes, and their relation to compression strength, there are very limited investigations of how pallet characteristics can affect the box compression strength. For example, there has been studies on the effect of relative humidity and temperature on corrugated [8][9] and there have been investigations on compression strength of boxes in regards to stacking strength, edge-loads, and unitized boxes [10] [11] [12] [13] [14] [15]. There are multiple factors of pallet design that could have a possible effect on the box compression strength, such as, pallet stiffness, pallet gaps, or box location on the pallet.

In 2016, Baker performed a similar study based on pallet stiffness and pallet gap on the effect of box compression strength [16]. He found that when there is no pallet gap, the pallet stiffness has a significant effect on the compression strength on the box. However, when a pallet gap was introduced, the pallet stiffness had an effect on compression strength of the box. The study concluded that the box compression strength could possibly be affected by the rotation of the top deckboard of the pallet and not completely on the deflection. The present study also confirms that pallet stiffness does not have an effect on box compression strength when a pallet gap is present. In 2011, Singh et. al. conducted an experiment where it was concluded that the compression strength of palletized empty corrugated boxes on a CHEP pallet is higher than the compression strength of palletized empty corrugated boxes on a Grocery Manufacturers Association (GMA) specified wood pallet [15]. However, because many parameters are different between a GMA style and a CHEP pallet including pallet style, pallet gaps, pallet deck stiffness, span between stringers or block, it is impossible to determine the exact cause of the reduction in compression strength.

## 3.3. Objective

The main objective of this study was to evaluate the combined effect of pallet deckboard deflection and twist on the compression strength of corrugated boxes by using different pallet stiffnesses and percentages of supported length of the sidewall.

## 3.4. Boundary Conditions

This study was bounded by the following limitations:

- Only one type corrugated box.
- Only one box on the pallet. This means there is no interaction between multiple boxes.
- The box was centred on the deckboard.
- Only pallet segments were used instead of full pallets.
- Fixed platen loading conditions.
- The top deckboards of the pallet were secured to the stringer with screws instead of nails to ensure consistency.

## 3.5. Materials and Methods

### 3.5.1. Materials

#### 3.5.1.1 Corrugated Paperboard Boxes

Production grade Regular Slotted Container (RSC) type corrugated boxes with outside dimensions of 7.5 in. x 6 in. x 6 in. were supplied by Packaging Corporation of America (PCA) [8], Roanoke, VA. The boxes were manufactured from nominal 32 lb./in. edge crush test (ECT) value B-flute corrugated board with nominal board grade of 33/26/33 lb./ft$^2$. The boxes were shipped flat and were erected using a custom jig to ensure that each of the edges had a 90° angle. Two strips of hot melt adhesive were applied to each minor flap to glue the corrugated boxes together.

#### 3.5.1.2 Pallet Deckboard Segments

Pallet deckboard segments were assembled using Southern Pine boards free of visible defects to simulate different top deckboard stiffness treatments. The deckboard segments were built to a length of 20.75 in. and a width of 3.5 in. The top deckboard of the pallet segments consisted of three different thicknesses, 0.75 in., 0.50 in., and 0.38 in. The bottom deckboard of the pallet segments had a thickness of 0.75 in. regardless of top deckboard thickness. The top deckboard and bottom deckboard were attached to two wood stringers using counter sunk wood screws. The size of stringers was 3.63 in. x 1.5 in. x 3.38 in. The stiffness of the pallet segments and the stiffness of the top deck board segments were tested using a three-point bending test according to ASTM D143 (2000). A universal tester (MTS Model 244.22) equipped with a 5000-pound load cell was used for the three-point bending test. The loading rate was 0.5 in./min.

### 3.5.2. Methods

Two pallet segments with the measured length and width of 20.75 in. x 3.5 in. were placed side by side with a specific gap between them in an MTS universal testing machine (Model 244.22). Two linear variable differential transformer (LVDTs) (Model 1000 HR-DC) were used to measure the deflection at the outside edge of the pallet segment where the LVDTs were aligned with the length panel and 0.25 in. into the outside width of the pallet segment while another two LVDTs (Model 200 HR-DC) were used to measure the deflection 0.25 in. into the inside width of the pallet segment where the length of the box touched the pallet segment. All four LVDTs were screwed down to plywood boards that were bolted to the MTS machine. This prevented any movement of the LVDTs from affecting the deflection measurements. The corrugated box was centered on top of the pallet segments once the pallet segments were placed a specific distance apart. However, there were two offset test set-ups where the corrugated box was not centered on the pallet segment. The distance between the pallet segments was changed to represent different percentages of the length of the sidewall that was supported. The various percentages of supported length of the sidewall tested are defined in Table 7 and may be seen in Figure 18. The test was conducted until the box failed according the ultimate load on the load/deflection curve displayed on the software. The test set-up is presented in Figure 18. The offsets tested are listed in Table 8 and may be seen in Figure 19 and Figure 20.

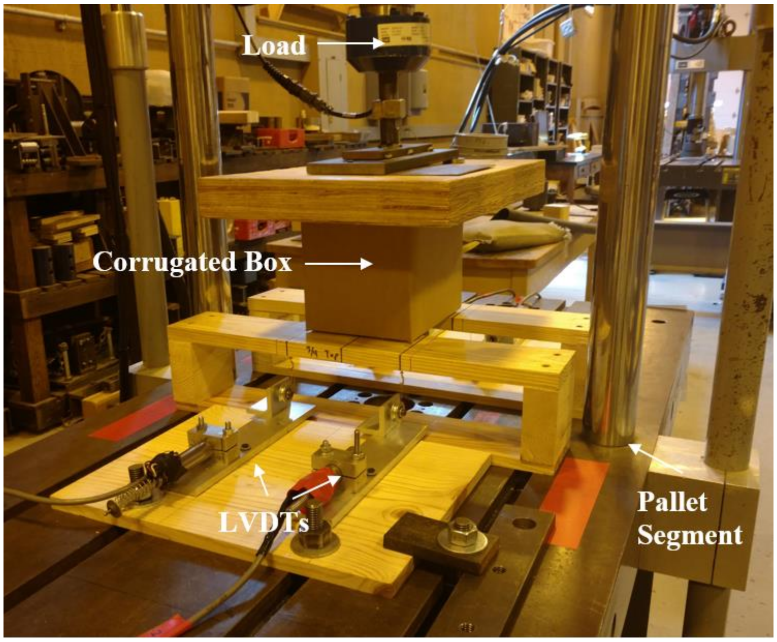


**Figure 18.** Experimental setup for the compression strength evaluation using two pallet segments.

3.6. Experimental Design

**Table 7.** Experimental design to investigate the effect of top deckboard twist on box compression strength

| TDB Thickness (in.) | Percentage of Length of Sidewall Supported | | | | | |
|---|---|---|---|---|---|---|
| | **93%** | **82%** | **70%** | **47%** | **23%** | **12%** |
| **0.75** | 10 | 10 | 10 | 10 | 10 | 10 |
| **0.50** | 10 | 10 | 10 | 10 | 10 | 10 |
| **0.38** | 10 | 10 | 10 | 10 | 10 | 10 |
| **Total Tests** | 180 | | | | | |

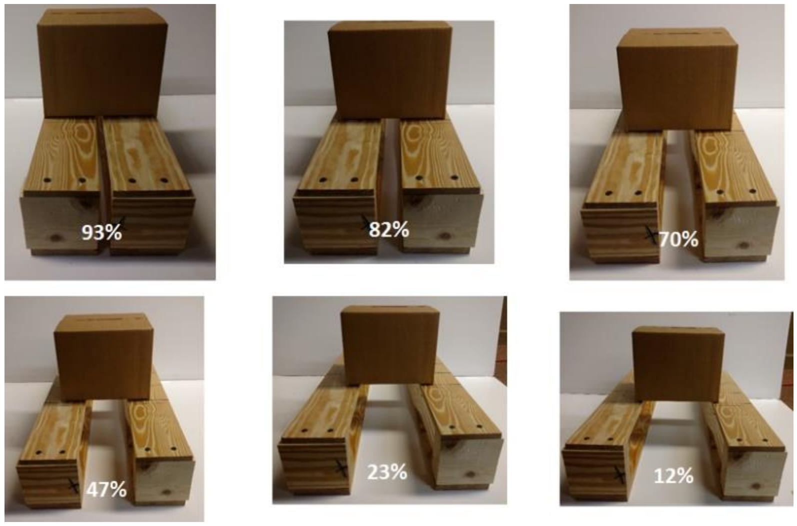


**Figure 19.** Percentage of length of sidewall supported investigated.

**Table 8.** Experimental design of box location offsets used to investigate the effect of pallet stiffness on box compression strength when 47% of the length of sidewall is supported.

| **TDB Thickness (in.)** | **Pallet Offset (in.)** | |
|---|---|---|
| | **0.44** | **3.06** |
| **0.75** | 10 | 10 |
| **0.50** | 10 | 10 |
| **0.38** | 10 | 10 |
| **Total Tests** | 60 | |


**Figure 20.** Offset investigated when 47% of length of sidewall was supported.

## 3.7. Statistical Analysis

A one-way Analysis of Variance (ANOVA) test at alpha 0.05 was performed on each test sample combination to analyze the effect of percent of length of sidewall supported within pallet stiffness on the compression strength of the corrugated box. Assumption tests, such as normality, homogeneity of variances, and independence of observations were completed to ensure the applicability of the ANOVA test. ANOVA was also chosen because there was one continuous response and multiple categorical predictors. Post hoc Tukey's honest significant difference (HSD) was conducted to evaluate any level of significant differences in the test results. The statistical analysis software SAS JMP Pro 12® [9], was utilized to conduct the statistical analysis. The ANOVA equation can be seen below [Equation 1].

*Equation 1:* $y_{ijkr} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijr}$

Where:

$y_{ijkr}$ = box failure load, $\mu$ = overall mean, $\alpha_i$ = effect of $i^{th}$ level of pallet stiffness, $\beta_j$ = effect of $j^{th}$ level of supported length of sidewall, $(\alpha\beta)_{ij}$ = joint effect of $i^{th}$ level of pallet stiffness and $j^{th}$ level of pallet gap, and $\varepsilon_{ijr}$ = random error of all groups.

## 3.8. Results and Discussion

The results of the measurements are presented in Table 9. An ANOVA test was run to investigate the effect of pallet stiffness on the compression strength of the corrugated box. It was found that at an alpha level of 0.05 there was no significant difference between the compression strength of the box measured using different pallet stiffnesses..

The effect of the amount of length of sidewall supported on the vertical compression strength of the box was investigated using a Tukey HSD test using alpha 0.05 significance (Table 9). The results of the statistical analysis showed overlap between the box compression strength values measured for the different percentages of supported sidewall length. However, the compression strength of the boxes with 12% of the length of the sidewall supported was significantly different from the strength of the boxes with 23% of the length of sidewall supported.

**Table 9.** Average failure load of the corrugated box based on percent of supported sidewall length and pallet stiffness.

| Supported length of sidewall (%) | Pallet Stiffness | | | | | |
|---|---|---|---|---|---|---|
| | Low | | Medium | | High | |
| | Average Failure Load (lbs) | Tukey's HSD | Average Failure Load (lbs) | Tukey's HSD | Average Failure Load (lbs) | Tukey's HSD |
| 93 | 244.2 (22.9) | AB | 242.6 (16.7) | BC | 244.7 (16.7) | AB |
| 82 | 253.5 (16.1) | A | 262.0 (17.7) | AB | 250.8 (21.2) | AB |
| 70 | 262.5 (27.1) | A | 268.2 (12.2) | A | 269.2 (15.6) | A |
| 47 | 238.9 (13.2) | AB | 247.7 (20.9) | AB | 244.2 (9.2) | AB |
| 23 | 218.8 (17.3) | BC | 224.1 (16.7) | CD | 228.5 (30.9) | BC |
| 12 | 206.7 (15.3) | C | 202.9 (12.8) | D | 210.2 (16.2) | C |

Note: Numbers in parenthesis are standard deviation values.
[1]Results not connected by the same letter were significantly different based on Tukey's HSD at an alpha level of 0.05.

The results of the experiment for the different percent of length of sidewall supported and pallet stiffness combinations and are presented in Figure 21. The box compression strength appears to increase up to when 70% of the length of the sidewall is supported and then decreases. The greatest reduction in box compression strength of 24.3% was observed between when 70% and 12% of the length of sidewall was supported using the medium stiffness pallet. Though there is no linear correlation between the amount of sidewall supported and the compression strength, it seems that the combination of the amount of sidewall supported with the twist in the top deckboard together have an effect on the compression strength of the box. The highest box compression strength was found when there was no twist present among the deckboards. The pallet stiffness also did not have an effect on the compression strength of the box when there was a pallet gap present and the deckboards were twisting. Baker also investigated the effect of pallet gaps on box compression strength and found that pallet stiffness does not have an effect on the compression strength when there is a pallet gap present [16]. He also found that the box compression strength increases then decreases as the pallet gap increases. The results found in this study follow a similar trend to what Baker had investigated in 2016 [17]. Both studies find that the greatest compression strength occurs when approximately 70% of the sidewall is supported.

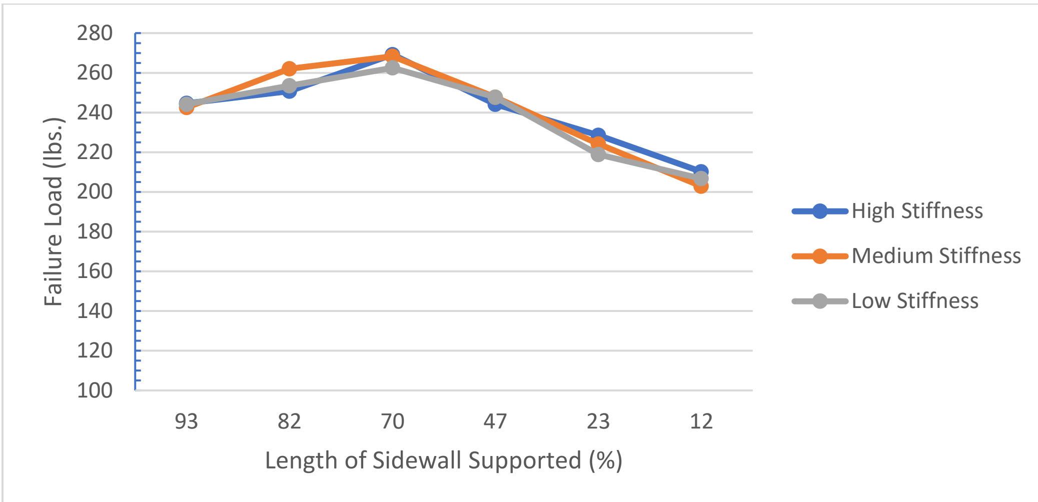


**Figure 21.** Corrugated box compression strength as a function of percent of sidewall length supported and pallet stiffness.

Using the measurements of the outside and inside pallet deckboard deflection, the twist of the top deckboards was calculated and presented in Figure 22. For 70%, 82%, and 93% of box support, the tilt angle is positive and the top deckboard is twisting away from the box, as if pushing the box edges outward. The twist became negative as 47% and less of the box was supported. With a negative twist, the top deckboard was pushing the box inward towards the center of the pallet segments creating a cradle effect on the box. The graphic representation of the negative and positive twist can be seen in Figure 23. When the other parameters were fixed, no correlation was found between the deckboard twist and the box compression strength during this investigation. An ANOVA test was run to investigate the effect of box offset on box compression strength. Table 10 displays the ANOVA results along with the box compression strength between a box that has an offset and a box that does not have an offset when placed on the pallet segments. The results show that at an alpha level of 0.05 there is no significant difference in box compression strength between having an offset present and not having an offset present.

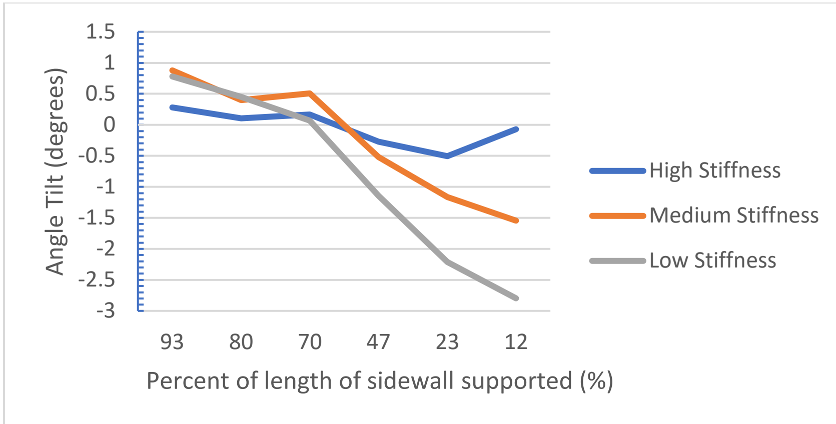


**Figure 22.** Angle twist of top deckboard based on percentage of length of sidewall supported and pallet stiffness.

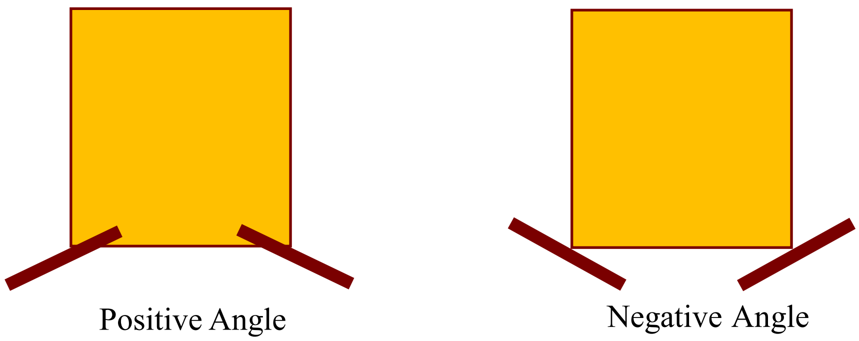


**Figure 23.** Graphic representation of the mode of pallet top deckboard twist on corrugated box.

**Table 10.** Average failure load based on pallet stiffness and box offset.

| Offset | Pallet Stiffness | | | | | |
|---|---|---|---|---|---|---|
| | Low | | Medium | | High | |
| | Failure Load (lbs) | Tukey's HSD | Failure Load (lbs) | Tukey's HSD | Failure Load (lbs) | Tukey's HSD |
| 0 in. | 238.9 (13.2) | A | 247.7 (20.9) | A | 244.4 (9.2) | A |
| 0.44 in. | 227.8 (16.3) | A | 226.6 (14.5) | AB | 231.9 (20.9) | A |
| 3.06 in. | 236.9 (7.3) | A | 243.0 (14.6) | B | 238.5 (22.9) | A |

Note: Numbers in parenthesis are standard deviation values.
[1]Results not connected by the same letter were significantly different based on Tukey's HSD at an alpha level of 0.05.

## 3.9. Conclusions

From this experiment, the following conclusions may be drawn:

(1) Pallet top deckboard stiffness and the resulting pallet deflection does not have a statistically significant effect on the compression strength of the corrugated box when there are any pallet gaps present.

(2) The percent of length of sidewall supported and the consequent twist angle only has a significant effect on the box compression strength when 23% and 12% of the length of the sidewall was supported. Compared to the scenario resulting the greatest box compression strength (70% supported sidewall length), the strength of the corrugated box decreased by 16.5% and 24.3% when 23% and 12% of the length of the sidewall was supported, respectively.

(3) Although, the pallet deckboard increased as the pallet top deckboard stiffness decreased, no linear correlation between the twist and the compression strength of the box was found.

(4) The results indicate that the stiffness reduction of the pallet deck does not adversely influence the strength of the corrugated box. In addition, the gap between pallet deckboards only have an adverse effect if less than 12% of the length of the sidewall is unsupported.

(5) There was no significant difference between the box compression strength of the corrugated box that had an offset and the corrugated box that did not have an offset when placed on the pallet segments.

## 3.10. References

[1] Twede, D. *The History of Corrugated Fiberboard Shipping Containers*. 2007, pp. 1–6.

[2] Bureau, US. "Census.Gov". *Census.gov*. 2016. Web. 9 Sept. 2016.

[3] Maltenfort, GG. *Corrugated Shipping Containers: An Engineering Approach*, Jelmar Publishing Co: Plainview, NY, 1996.

[4] Kellicutt, K. *Effect of Contents and Load Bearing Surface on Compression Strength and Stacking Life of Corrugated Containers*; 1963 (46.1), 151A–154A.

[5] Frank, Benjamin. Corrugated Box Compression—A Literature Survey. *Packaging Technology and Science* 2014 (27), pp. 105-128.

[6] Kutt H, Mithel BB. Studies on compressive strength of corrugated containers. *TAPPI* 1968 (51.4): pp. 79.

[7] Maltenfort GG. *Performance and Evaluation of Shipping Containers*, Jelmar Publishing Co.: Plainview, NY, 1989.

[8] Wink WA. The effect of relative humidity and temperature on paper properties. *TAPPI* 1961 (44.6): 171A–180A.

[9] Whitsitt WJ, McKee RC. Effect of relative humidity and temperature on stacking performance. IPC report project 2695–9, Nov 10, 1972.

[10] Stott, RA. Compression and stacking strength of corrugated fiberboard containers. APPITA 1959 (13.2): pp. 84–86.

[11] Kellicutt, KQ. Note No. 13: *Compressive strength of boxes part 3, Package Engineering*, February 1960.

[12] Miles, JG. *Compressive strength of corrugated containers: An interlaboratory study*. Mater. Res. Standards 1966, pp.142–146.

[13] Carlson, TA. Factors affecting the compressive strength of fiber boxes. *Fibre Containers* 1941 (26.3), pp. 28–35.

[14] Hahn, EK, De Ruvo, A, Westerlind BS, Carlsson LA. *Compressive strength of edge-loaded corrugated board panels*. Exper. Mech., 1992, pp.259– 265.

[15] Singh, SP, Singh J, and Saha K. "Effect Of Palletized Box Offset On Compression Strength Of Unitized And Stacked Empty Corrugated Fiberboard Boxes". *Journal of Applied Packaging Research* 2011 (5.3); pp. 157-167.

[16] Baker M, Horvath L, White MS. Effect of Pallet Deckboard Stiffness on Corrugated Box Compression Strength. *Packaging Technology and Science* 2016 (29.4-5), pp. 263-274.

[17] Baker, Matthew, Laszlo Horvath, and Marshall White. "Predicting the Effect of Gaps between Pallet Deckboards on Compression Strength of Corrugated Boxes". *Journal of Applied Packaging Research*, 2016 (8.3), pp. 30-42.

## Chapter 5: Recommendations for Future Studies

There are multiple investigations that are still necessary in order to fully understand load-bridging and package to pallet interactions. Overall, there should be a continuation of studies that investigate what factors do and do not have a significant effect on pallet deflection. Based on the observations of this research the following suggestions for future study can be made:

**Chapter 2: The Investigation of Effect of Package Content of Pallet Deflection**

- It would be interesting to reverse the project to see how the package behavior can change in this scenario. The effect of package content on box compression strength during pallet deflection would allow us to further investigate what is happening to the package itself.
- The effect of stretch wrap and package content on pallet deflection would allow us to see how a real-life scenario unit load would behave with different package contents.
- The effect of the coefficient of friction on pallet deflection would be a good next step considering the results from the study in this paper may lead us to believe the coefficient of friction could be a factor in load-bridging.
- The effect of box aspect ratio on pallet deflection is another suggestion to see how different amounts of the box area being supported could affect load-bridging.

**Chapter 3: The Investigation of the Effect of Top Deckboard Twist on Box Compression Strength**

- Perform a similar investigation with multiple boxes. Boxes are rarely shipped alone and testing with multiple boxes will give a more realistic scenario of how boxes are stored. Boxes also behave differently when they are stacked together. This could lead to different results than the ones found for a single box test.
- Investigate how different flute sizes and box styles can be affected by pallet gaps to broaden the knowledge on how package strength can be effected by pallet characteristics.

**Appendix A:** Results of statistical analysis for analyzing the effect of package content on pallet deflection

**Table 11.** ANOVA results for the effects of package size, package content, and pallet stiffness on pallet deflection.

| **Source** | **DF** | **Sum of Squares** | **F Ratio** | **Prob > F** |
|---|---|---|---|---|
| Pallet Stiffness | 2 | 6.4039613 | 3905.171 | <.0001* |
| Package Size | 2 | 1.4567665 | 888.3442 | <.0001* |
| Pallet Stiffness*Package Size | 4 | 0.3042377 | 92.7629 | <.0001* |
| Package Content | 2 | 0.0007896 | 0.4815 | 0.6185 |
| Pallet Stiffness*Package Content | 4 | 0.0211148 | 6.4380 | <.0001* |
| Package Size*Package Content | 4 | 0.0039661 | 1.2093 | 0.3078 |
| Pallet Stiffness*Package Size*Package Content | 8 | 0.0038959 | 0.5939 | 0.7824 |
| Trial | 2 | 0.0002650 | 0.1616 | 0.8509 |

*Statistically significant at the 95% of significance level

**Table 12.** Raw deflection data for all trials of rigid package content.

| Stiffness | Box Size | Trial 3 Rigid Def. (in.) | Trial 2 Rigid Def. (in.) | Trial 1 Rigid Def. (in.) |
|---|---|---|---|---|
| High | 5 | 0.189 | 0.188 | 0.200 |
| | 5 | 0.181 | 0.187 | 0.214 |
| | 5 | 0.182 | 0.187 | 0.237 |
| | 10 | 0.149 | 0.141 | 0.140 |
| | 10 | 0.145 | 0.145 | 0.170 |
| | 10 | 0.148 | 0.151 | 0.150 |
| | 20 | 0.131 | 0.091 | 0.081 |
| | 20 | 0.130 | 0.113 | 0.082 |
| | 20 | 0.121 | 0.128 | 0.070 |
| Medium | 5 | 0.360 | 0.373 | 0.540 |
| | 5 | 0.391 | 0.375 | 0.500 |
| | 5 | 0.371 | 0.389 | 0.520 |
| | 10 | 0.281 | 0.270 | 0.380 |
| | 10 | 0.288 | 0.290 | 0.380 |
| | 10 | 0.269 | 0.283 | 0.360 |
| | 20 | 0.188 | 0.187 | 0.250 |
| | 20 | 0.187 | 0.192 | 0.280 |
| | 20 | 0.176 | 0.171 | 0.220 |
| low | 5 | 0.686 | 0.684 | 0.640 |
| | 5 | 0.684 | 0.692 | 0.670 |
| | 5 | 0.689 | 0.644 | 0.690 |
| | 10 | 0.558 | 0.514 | 0.560 |
| | 10 | 0.544 | 0.533 | 0.550 |
| | 10 | 0.558 | 0.599 | 0.570 |
| | 20 | 0.394 | 0.434 | 0.360 |
| | 20 | 0.415 | 0.379 | 0.340 |
| | 20 | 0.392 | 0.397 | 0.360 |

**Table 13.** Raw deflection data for all trials of flexible package content.

| Stiffness | Box Size | Trial 3 Flexible Def. (in.) | Trial 2 Flexible Def. (in.) | Trial 1 Flexible Def. (in.) |
|---|---|---|---|---|
| High | 5 | 0.198 | 0.194 | 0.129 |
| | 5 | 0.193 | 0.197 | 0.106 |
| | 5 | 0.190 | 0.188 | 0.104 |
| | 10 | 0.157 | 0.154 | 0.071 |
| | 10 | 0.150 | 0.160 | 0.071 |
| | 10 | 0.156 | 0.152 | 0.087 |
| | 20 | 0.119 | 0.127 | 0.029 |
| | 20 | 0.128 | 0.124 | 0.034 |
| | 20 | 0.124 | 0.120 | 0.034 |
| Medium | 5 | 0.427 | 0.420 | 0.458 |
| | 5 | 0.423 | 0.422 | 0.515 |
| | 5 | 0.419 | 0.433 | 0.484 |
| | 10 | 0.314 | 0.319 | 0.305 |
| | 10 | 0.316 | 0.300 | 0.349 |
| | 10 | 0.315 | 0.313 | 0.314 |
| | 20 | 0.204 | 0.199 | 0.224 |
| | 20 | 0.205 | 0.198 | 0.211 |
| | 20 | 0.204 | 0.205 | 0.232 |
| low | 5 | 0.671 | 0.680 | 0.655 |
| | 5 | 0.667 | 0.650 | 0.691 |
| | 5 | 0.673 | 0.679 | 0.573 |
| | 10 | 0.588 | 0.563 | 0.515 |
| | 10 | 0.570 | 0.578 | 0.534 |
| | 10 | 0.566 | 0.575 | 0.571 |
| | 20 | 0.407 | 0.411 | 0.315 |
| | 20 | 0.414 | 0.412 | 0.374 |
| | 20 | 0.415 | 0.401 | 0.370 |

**Table 14.** Raw deflection data for all trials of semi-rigid content.

| Stiffness | Box Size | Trial 3 Semi-Rigid Def. (in.) | Trial 2 Semi-Rigid Def. (in.) | Trial 1 Semi-Rigid Def. (in.) |
|---|---|---|---|---|
| High | 5 | 0.189 | 0.186 | 0.196 |
| | 5 | 0.190 | 0.192 | 0.187 |
| | 5 | 0.194 | 0.188 | 0.192 |
| | 10 | 0.145 | 0.153 | 0.158 |
| | 10 | 0.154 | 0.149 | 0.146 |
| | 10 | 0.151 | 0.152 | 0.153 |
| | 20 | 0.129 | 0.130 | 0.127 |
| | 20 | 0.131 | 0.128 | 0.132 |
| | 20 | 0.126 | 0.121 | 0.125 |
| Medium | 5 | 0.408 | 0.399 | 0.382 |
| | 5 | 0.402 | 0.410 | 0.389 |
| | 5 | 0.393 | 0.402 | 0.376 |
| | 10 | 0.308 | 0.289 | 0.277 |
| | 10 | 0.286 | 0.306 | 0.300 |
| | 10 | 0.304 | 0.292 | 0.281 |
| | 20 | 0.191 | 0.195 | 0.210 |
| | 20 | 0.205 | 0.202 | 0.198 |
| | 20 | 0.209 | 0.198 | 0.208 |
| low | 5 | 0.676 | 0.662 | 0.662 |
| | 5 | 0.665 | 0.680 | 0.688 |
| | 5 | 0.670 | 0.665 | 0.679 |
| | 10 | 0.573 | 0.576 | 0.564 |
| | 10 | 0.562 | 0.569 | 0.577 |
| | 10 | 0.575 | 0.566 | 0.582 |
| | 20 | 0.405 | 0.399 | 0.408 |
| | 20 | 0.398 | 0.397 | 0.396 |
| | 20 | 0.395 | 0.409 | 0.392 |

**Appendix B:** Results of statistical analysis for analyzing the effect of top deckboard rotation on corrugated box compression strength

**Table 15.** ANOVA results for the effect of pallet stiffness and percent of length of sidewall supported on box compression strength.

| Source | DF | Sum of Squares | F. Ratio | Prob > F |
|---|---|---|---|---|
| TDB Thickness (in.) | 2 | 587.778 | 0.6379 | 0.5297 |
| % of sidewall length supported | 1 | 46762.827 | 101.4944 | <.0001* |
| TDB thickness (in.)*% of box area supported | 2 | 392.128 | 0.4255 | 0.6541 |

*Statistically significant at the 95% of significance level

**Table 16.** Raw Data for failure load, deflection, and twist angle for 0.75 in. TDB thickness.

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 | Angle 2 |
|---|---|---|---|---|---|---|---|
| 6.625 | 208 | 0.026 | 0.027 | 0.064 | 0.065 | -0.718 | -0.726 |
| 6.625 | 233 | 0.032 | 0.033 | 0.068 | 0.069 | -0.678 | -0.698 |
| 6.625 | 214 | 0.025 | 0.026 | 0.066 | 0.066 | -0.772 | -0.774 |
| 6.625 | 201 | 0.025 | 0.025 | 0.057 | 0.056 | -0.606 | -0.592 |
| 6.625 | 240 | 0.023 | 0.023 | 0.063 | 0.061 | -0.762 | -0.723 |
| 6.625 | 200 | 0.023 | 0.023 | 0.055 | 0.054 | -0.613 | -0.601 |
| 6.625 | 191 | 0.026 | 0.027 | 0.056 | 0.055 | -0.578 | -0.529 |
| 6.625 | 199 | 0.023 | 0.024 | 0.053 | 0.051 | -0.566 | -0.519 |
| 6.625 | 197 | -0.008 | -0.007 | 0.050 | 0.045 | -1.106 | -0.995 |
| 6.625 | 219 | 0.024 | 0.024 | 0.058 | 0.057 | -0.646 | -0.615 |
| 5.75 | 217 | 0.020 | 0.021 | 0.047 | 0.044 | -0.516 | -0.445 |
| 5.75 | 211 | 0.032 | 0.033 | 0.060 | 0.058 | -0.536 | -0.481 |
| 5.75 | 203 | 0.032 | 0.033 | 0.058 | 0.056 | -0.494 | -0.442 |
| 5.75 | 240 | 0.034 | 0.035 | 0.064 | 0.063 | -0.572 | -0.529 |
| 5.75 | 287 | 0.041 | 0.043 | 0.071 | 0.072 | -0.583 | -0.561 |
| 5.75 | 250 | 0.030 | 0.032 | 0.062 | 0.061 | -0.605 | -0.562 |
| 5.75 | 202 | 0.025 | 0.028 | 0.048 | 0.047 | -0.444 | -0.374 |
| 5.75 | 266 | 0.035 | 0.036 | 0.069 | 0.068 | -0.650 | -0.613 |
| 5.75 | 193 | 0.030 | 0.031 | 0.054 | 0.053 | -0.452 | -0.432 |
| 5.75 | 216 | 0.024 | 0.026 | 0.046 | 0.045 | -0.427 | -0.374 |
| 4 | 251 | 0.037 | 0.037 | 0.053 | 0.049 | -0.292 | -0.214 |
| 4 | 237 | 0.048 | 0.051 | 0.059 | 0.057 | -0.196 | -0.113 |
| 4 | 259 | 0.032 | 0.033 | 0.047 | 0.044 | -0.270 | -0.199 |
| 4 | 242 | 0.030 | 0.030 | 0.050 | 0.045 | -0.381 | -0.284 |
| 4 | 244 | 0.027 | 0.027 | 0.047 | 0.042 | -0.392 | -0.286 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 4 | 247 | 0.030 | 0.032 | 0.050 | 0.045 | -0.375 | -0.259 |
| 4 | 238 | 0.042 | 0.044 | 0.057 | 0.054 | -0.302 | -0.189 |
| 4 | 251 | 0.034 | 0.037 | 0.053 | 0.049 | -0.368 | -0.234 |
| 4 | 247 | 0.043 | 0.045 | 0.061 | 0.058 | -0.343 | -0.239 |
| 4 | 226 | 0.039 | 0.041 | 0.055 | 0.052 | -0.307 | -0.210 |
| 2.25 | 265 | 0.065 | 0.068 | 0.055 | 0.053 | 0.182 | 0.287 |
| 2.25 | 269 | 0.062 | 0.064 | 0.052 | 0.050 | 0.194 | 0.270 |
| 2.25 | 302 | 0.067 | 0.070 | 0.063 | 0.061 | 0.076 | 0.173 |
| 2.25 | 272 | 0.057 | 0.060 | 0.053 | 0.051 | 0.075 | 0.177 |
| 2.25 | 285 | 0.065 | 0.069 | 0.055 | 0.056 | 0.201 | 0.257 |
| 2.25 | 260 | 0.060 | 0.063 | 0.056 | 0.056 | 0.085 | 0.124 |
| 2.25 | 275 | 0.057 | 0.060 | 0.056 | 0.056 | 0.025 | 0.079 |
| 2.25 | 247 | 0.056 | 0.061 | 0.050 | 0.056 | 0.115 | 0.093 |
| 2.25 | 260 | 0.061 | 0.067 | 0.050 | 0.055 | 0.223 | 0.218 |
| 2.25 | 257 | 0.061 | 0.066 | 0.049 | 0.055 | 0.223 | 0.216 |
| 1.375 | 234 | 0.056 | 0.059 | 0.051 | 0.051 | 0.108 | 0.166 |
| 1.375 | 262 | 0.057 | 0.060 | 0.053 | 0.053 | 0.079 | 0.131 |
| 1.375 | 263 | 0.036 | 0.041 | 0.042 | 0.042 | -0.108 | -0.013 |
| 1.375 | 232 | 0.056 | 0.057 | 0.052 | 0.048 | 0.065 | 0.167 |
| 1.375 | 230 | 0.057 | 0.059 | 0.052 | 0.048 | 0.096 | 0.198 |
| 1.375 | 283 | 0.064 | 0.066 | 0.060 | 0.057 | 0.078 | 0.180 |
| 1.375 | 277 | 0.064 | 0.063 | 0.056 | 0.058 | 0.156 | 0.101 |
| 1.375 | 263 | 0.064 | 0.064 | 0.054 | 0.056 | 0.146 | 0.113 |
| 1.375 | 224 | 0.057 | 0.058 | 0.049 | 0.051 | 0.160 | 0.117 |
| 1.375 | 240 | 0.062 | 0.062 | 0.056 | 0.059 | 0.111 | 0.054 |
| 0.5 | 240 | 0.060 | 0.060 | 0.045 | 0.045 | 0.294 | 0.288 |
| 0.5 | 256 | 0.066 | 0.064 | 0.052 | 0.052 | 0.264 | 0.239 |
| 0.5 | 248 | 0.069 | 0.069 | 0.051 | 0.051 | 0.342 | 0.347 |
| 0.5 | 215 | 0.061 | 0.061 | 0.042 | 0.044 | 0.368 | 0.337 |
| 0.5 | 231 | 0.058 | 0.058 | 0.044 | 0.044 | 0.268 | 0.268 |
| 0.5 | 266 | 0.071 | 0.071 | 0.054 | 0.055 | 0.319 | 0.316 |
| 0.5 | 268 | 0.068 | 0.068 | 0.051 | 0.051 | 0.331 | 0.337 |
| 0.5 | 254 | 0.064 | 0.064 | 0.051 | 0.049 | 0.256 | 0.278 |
| 0.5 | 234 | 0.061 | 0.060 | 0.052 | 0.051 | 0.159 | 0.164 |
| 0.5 | 235 | 0.055 | 0.057 | 0.045 | 0.044 | 0.194 | 0.249 |
| 0.4375 | 217 | 0.007 | 0.006 | 0.048 | 0.045 | -0.782 | -0.739 |
| 0.4375 | 201 | 0.005 | 0.005 | 0.044 | 0.042 | -0.739 | -0.693 |
| 0.4375 | 250 | -0.007 | -0.007 | 0.049 | 0.046 | -1.070 | -1.024 |
| 0.4375 | 208 | 0.015 | 0.011 | 0.058 | 0.056 | -0.819 | -0.868 |
| 0.4375 | 213 | 0.000 | 0.001 | 0.044 | 0.044 | -0.853 | -0.805 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 0.4375 | 227 | 0.001 | 0.000 | 0.051 | 0.052 | -1.030 | -1.070 |
| 0.4375 | 255 | 0.002 | 0.002 | 0.056 | 0.057 | -1.027 | -1.050 |
| 0.4375 | 249 | -0.003 | -0.004 | 0.049 | 0.045 | -0.991 | -0.927 |
| 0.4375 | 246 | -0.009 | -0.009 | 0.046 | 0.040 | -1.059 | -0.925 |
| 0.4375 | 253 | -0.009 | -0.009 | 0.049 | 0.046 | -1.124 | -1.037 |
| 3.0625 | 282 | 0.070 | 0.069 | 0.059 | 0.046 | 0.209 | 0.441 |
| 3.0625 | 260 | 0.065 | 0.066 | 0.041 | 0.035 | 0.462 | 0.588 |
| 3.0625 | 242 | 0.054 | 0.054 | 0.051 | 0.042 | 0.063 | 0.239 |
| 3.0625 | 236 | 0.057 | 0.056 | 0.045 | 0.040 | 0.214 | 0.311 |
| 3.0625 | 207 | 0.060 | 0.064 | 0.037 | 0.033 | 0.437 | 0.599 |
| 3.0625 | 217 | 0.053 | 0.057 | 0.044 | 0.031 | 0.161 | 0.512 |
| 3.0625 | 250 | 0.063 | 0.066 | 0.056 | 0.048 | 0.120 | 0.348 |
| 3.0625 | 212 | 0.050 | 0.053 | 0.031 | 0.025 | 0.368 | 0.528 |
| 3.0625 | 244 | 0.057 | 0.060 | 0.050 | 0.039 | 0.134 | 0.414 |
| 3.0625 | 235 | 0.060 | 0.063 | 0.032 | 0.025 | 0.523 | 0.732 |

**Table 17.** Raw data for failure load, deflection, and twist angle for 0.5 in. TDB thickness.

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 6.625 | 196 | 0.066 | 0.074 | 0.141 | 0.144 | -1.439 | -1.354 |
| 6.625 | 232 | 0.072 | 0.085 | 0.178 | 0.183 | -2.020 | -1.881 |
| 6.625 | 200 | 0.070 | 0.078 | 0.153 | 0.163 | -1.589 | -1.630 |
| 6.625 | 198 | 0.052 | 0.063 | 0.137 | 0.142 | -1.619 | -1.512 |
| 6.625 | 198 | 0.064 | 0.072 | 0.132 | 0.140 | -1.310 | -1.312 |
| 6.625 | 192 | 0.053 | 0.062 | 0.132 | 0.139 | -1.505 | -1.457 |
| 6.625 | 212 | 0.060 | 0.073 | 0.152 | 0.158 | -1.751 | -1.619 |
| 6.625 | 196 | 0.059 | 0.067 | 0.131 | 0.138 | -1.376 | -1.341 |
| 6.625 | 191 | 0.062 | 0.071 | 0.133 | 0.142 | -1.347 | -1.357 |
| 6.625 | 214 | 0.060 | 0.072 | 0.154 | 0.160 | -1.795 | -1.686 |
| 5.75 | 213 | 0.092 | 0.098 | 0.148 | 0.151 | -1.065 | -1.003 |
| 5.75 | 224 | 0.096 | 0.102 | 0.148 | 0.152 | -1.000 | -0.948 |
| 5.75 | 243 | 0.089 | 0.101 | 0.172 | 0.173 | -1.380 | -0.948 |
| 5.75 | 219 | 0.094 | 0.100 | 0.148 | 0.153 | -1.023 | -1.026 |
| 5.75 | 224 | 0.090 | 0.098 | 0.146 | 0.151 | -1.074 | -1.018 |
| 5.75 | 186 | 0.050 | 0.057 | 0.101 | 0.105 | -0.974 | -0.906 |
| 5.75 | 229 | 0.093 | 0.100 | 0.153 | 0.160 | -1.146 | -1.135 |
| 5.75 | 224 | 0.084 | 0.091 | 0.150 | 0.156 | -1.246 | -1.235 |
| 5.75 | 234 | 0.098 | 0.103 | 0.166 | 0.173 | -1.309 | -1.332 |
| 5.75 | 245 | 0.086 | 0.095 | 0.168 | 0.172 | -1.573 | -1.464 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 4 | 248 | 0.115 | 0.116 | 0.142 | 0.150 | -0.503 | -0.648 |
| 4 | 228 | 0.090 | 0.092 | 0.122 | 0.127 | -0.607 | -0.666 |
| 4 | 259 | 0.099 | 0.103 | 0.140 | 0.145 | -0.782 | -0.804 |
| 4 | 247 | 0.105 | 0.106 | 0.130 | 0.132 | -0.480 | -0.490 |
| 4 | 268 | 0.102 | 0.106 | 0.134 | 0.136 | -0.622 | -0.585 |
| 4 | 234 | 0.082 | 0.084 | 0.111 | 0.113 | -0.553 | -0.556 |
| 4 | 248 | 0.115 | 0.118 | 0.132 | 0.142 | -0.335 | -0.471 |
| 4 | 288 | 0.127 | 0.133 | 0.158 | 0.165 | -0.590 | -0.610 |
| 4 | 213 | 0.121 | 0.121 | 0.120 | 0.129 | 0.007 | -0.142 |
| 4 | 244 | 0.108 | 0.111 | 0.130 | 0.138 | -0.423 | -0.513 |
| 2.25 | 258 | 0.154 | 0.153 | 0.124 | 0.127 | 0.561 | 0.491 |
| 2.25 | 272 | 0.173 | 0.164 | 0.139 | 0.133 | 0.647 | 0.601 |
| 2.25 | 288 | 0.167 | 0.163 | 0.138 | 0.140 | 0.545 | 0.437 |
| 2.25 | 246 | 0.168 | 0.161 | 0.134 | 0.135 | 0.652 | 0.510 |
| 2.25 | 277 | 0.170 | 0.168 | 0.146 | 0.143 | 0.452 | 0.474 |
| 2.25 | 275 | 0.166 | 0.165 | 0.143 | 0.140 | 0.443 | 0.460 |
| 2.25 | 261 | 0.155 | 0.148 | 0.132 | 0.129 | 0.431 | 0.359 |
| 2.25 | 259 | 0.146 | 0.149 | 0.117 | 0.118 | 0.547 | 0.605 |
| 2.25 | 276 | 0.157 | 0.160 | 0.138 | 0.135 | 0.365 | 0.476 |
| 2.25 | 271 | 0.157 | 0.159 | 0.131 | 0.125 | 0.501 | 0.644 |
| 1.375 | 258 | 0.162 | 0.163 | 0.143 | 0.145 | 0.370 | 0.357 |
| 1.375 | 259 | 0.148 | 0.151 | 0.126 | 0.128 | 0.424 | 0.437 |
| 1.375 | 244 | 0.163 | 0.163 | 0.134 | 0.139 | 0.564 | 0.453 |
| 1.375 | 258 | 0.148 | 0.149 | 0.130 | 0.129 | 0.337 | 0.384 |
| 1.375 | 246 | 0.137 | 0.135 | 0.114 | 0.105 | 0.448 | 0.563 |
| 1.375 | 242 | 0.139 | 0.140 | 0.120 | 0.118 | 0.369 | 0.414 |
| 1.375 | 282 | 0.163 | 0.159 | 0.151 | 0.148 | 0.237 | 0.198 |
| 1.375 | 299 | 0.182 | 0.178 | 0.162 | 0.160 | 0.398 | 0.350 |
| 1.375 | 266 | 0.183 | 0.180 | 0.160 | 0.159 | 0.448 | 0.405 |
| 1.375 | 266 | 0.165 | 0.162 | 0.143 | 0.141 | 0.410 | 0.405 |
| 0.5 | 242 | 0.174 | 0.162 | 0.123 | 0.118 | 0.988 | 0.849 |
| 0.5 | 256 | 0.166 | 0.158 | 0.122 | 0.119 | 0.843 | 0.745 |
| 0.5 | 257 | 0.186 | 0.172 | 0.121 | 0.118 | 1.226 | 1.020 |
| 0.5 | 247 | 0.170 | 0.157 | 0.125 | 0.123 | 0.863 | 0.642 |
| 0.5 | 236 | 0.176 | 0.162 | 0.126 | 0.117 | 0.961 | 0.869 |
| 0.5 | 225 | 0.175 | 0.160 | 0.129 | 0.122 | 0.870 | 0.718 |
| 0.5 | 237 | 0.159 | 0.143 | 0.121 | 0.112 | 0.724 | 0.580 |
| 0.5 | 246 | 0.168 | 0.158 | 0.123 | 0.116 | 0.859 | 0.793 |
| 0.5 | 269 | 0.193 | 0.178 | 0.131 | 0.122 | 1.182 | 1.072 |
| 0.5 | 211 | 0.162 | 0.147 | 0.115 | 0.102 | 0.896 | 0.860 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 0.4375 | 216 | 0.056 | 0.066 | 0.140 | 0.151 | -1.608 | -1.631 |
| 0.4375 | 204 | 0.055 | 0.065 | 0.141 | 0.154 | -1.640 | -1.692 |
| 0.4375 | 237 | 0.050 | 0.063 | 0.155 | 0.161 | -2.000 | -1.879 |
| 0.4375 | 250 | 0.042 | 0.055 | 0.143 | 0.156 | -1.925 | -1.930 |
| 0.4375 | 218 | 0.032 | 0.043 | 0.126 | 0.131 | -1.805 | -1.693 |
| 0.4375 | 224 | 0.028 | 0.041 | 0.136 | 0.144 | -2.068 | -1.963 |
| 0.4375 | 230 | 0.045 | 0.058 | 0.155 | 0.158 | -2.092 | -1.907 |
| 0.4375 | 229 | 0.042 | 0.057 | 0.151 | 0.162 | -2.098 | -2.007 |
| 0.4375 | 213 | 0.034 | 0.051 | 0.154 | 0.167 | -2.293 | -2.215 |
| 0.4375 | 245 | 0.052 | 0.068 | 0.165 | 0.178 | -2.146 | -2.110 |
| 3.0625 | 236 | 0.158 | 0.154 | 0.117 | 0.125 | 0.791 | 0.550 |
| 3.0625 | 256 | 0.168 | 0.160 | 0.141 | 0.145 | 0.521 | 0.282 |
| 3.0625 | 275 | 0.201 | 0.193 | 0.147 | 0.155 | 1.033 | 0.717 |
| 3.0625 | 240 | 0.155 | 0.151 | 0.122 | 0.124 | 0.644 | 0.514 |
| 3.0625 | 231 | 0.160 | 0.156 | 0.125 | 0.118 | 0.663 | 0.727 |
| 3.0625 | 246 | 0.172 | 0.167 | 0.131 | 0.122 | 0.781 | 0.845 |
| 3.0625 | 240 | 0.160 | 0.156 | 0.125 | 0.119 | 0.662 | 0.717 |
| 3.0625 | 223 | 0.157 | 0.152 | 0.116 | 0.115 | 0.777 | 0.717 |
| 3.0625 | 234 | 0.175 | 0.170 | 0.135 | 0.127 | 0.772 | 0.813 |
| 3.0625 | 249 | 0.185 | 0.180 | 0.141 | 0.137 | 0.839 | 0.814 |

**Table 18.** Raw data for failure load, deflection, and twist angle for 0.375 in. TDB Thickness.

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 6.625 | 229 | 0.079 | 0.076 | 0.238 | 0.250 | -3.050 | -3.322 |
| 6.625 | 211 | 0.071 | 0.067 | 0.229 | 0.235 | -3.014 | -3.194 |
| 6.625 | 195 | 0.058 | 0.057 | 0.183 | 0.192 | -2.396 | -2.590 |
| 6.625 | 216 | 0.072 | 0.069 | 0.226 | 0.222 | -2.937 | -2.917 |
| 6.625 | 201 | 0.067 | 0.063 | 0.206 | 0.206 | -2.648 | -2.729 |
| 6.625 | 211 | 0.064 | 0.059 | 0.210 | 0.208 | -2.781 | -2.842 |
| 6.625 | 230 | 0.076 | 0.071 | 0.235 | 0.234 | -3.040 | -3.122 |
| 6.625 | 196 | 0.065 | 0.062 | 0.203 | 0.195 | -2.629 | -2.539 |
| 6.625 | 193 | 0.063 | 0.059 | 0.207 | 0.204 | -2.735 | -2.759 |
| 6.625 | 185 | 0.042 | 0.038 | 0.164 | 0.162 | -2.331 | -2.375 |
| 5.75 | 215 | 0.109 | 0.108 | 0.218 | 0.215 | -2.086 | -2.047 |
| 5.75 | 213 | 0.070 | 0.069 | 0.186 | 0.183 | -2.217 | -2.168 |
| 5.75 | 223 | 0.102 | 0.101 | 0.212 | 0.210 | -2.105 | -2.080 |
| 5.75 | 230 | 0.092 | 0.090 | 0.224 | 0.225 | -2.534 | -2.579 |
| 5.75 | 247 | 0.088 | 0.088 | 0.227 | 0.218 | -2.652 | -2.480 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 5.75 | 203 | 0.089 | 0.087 | 0.202 | 0.199 | -2.160 | -2.137 |
| 5.75 | 217 | 0.105 | 0.103 | 0.218 | 0.215 | -2.159 | -2.150 |
| 5.75 | 207 | 0.116 | 0.102 | 0.213 | 0.208 | -1.841 | -2.026 |
| 5.75 | 191 | 0.095 | 0.084 | 0.185 | 0.178 | -1.709 | -1.783 |
| 5.75 | 242 | 0.093 | 0.081 | 0.226 | 0.229 | -2.531 | -2.829 |
| 4 | 253 | 0.124 | 0.126 | 0.190 | 0.210 | -1.258 | -1.610 |
| 4 | 241 | 0.109 | 0.111 | 0.179 | 0.192 | -1.551 | -1.545 |
| 4 | 255 | 0.147 | 0.149 | 0.211 | 0.230 | -1.240 | -1.545 |
| 4 | 258 | 0.112 | 0.117 | 0.173 | 0.174 | -1.168 | -1.100 |
| 4 | 235 | 0.108 | 0.111 | 0.167 | 0.161 | -1.122 | -0.948 |
| 4 | 226 | 0.142 | 0.143 | 0.190 | 0.187 | -0.914 | -0.836 |
| 4 | 221 | 0.099 | 0.100 | 0.162 | 0.158 | -1.189 | -1.108 |
| 4 | 243 | 0.122 | 0.124 | 0.189 | 0.187 | -1.273 | -1.217 |
| 4 | 227 | 0.142 | 0.141 | 0.184 | 0.183 | -0.809 | -0.807 |
| 4 | 230 | 0.137 | 0.136 | 0.178 | 0.179 | -0.783 | -0.821 |
| 2.25 | 283 | 0.195 | 0.195 | 0.189 | 0.183 | 0.126 | 0.218 |
| 2.25 | 282 | 0.203 | 0.202 | 0.197 | 0.193 | 0.104 | 0.157 |
| 2.25 | 260 | 0.186 | 0.182 | 0.183 | 0.178 | 0.069 | 0.072 |
| 2.25 | 294 | 0.219 | 0.216 | 0.184 | 0.182 | 0.659 | 0.643 |
| 2.25 | 247 | 0.140 | 0.145 | 0.180 | 0.174 | -0.757 | -0.552 |
| 2.25 | 249 | 0.179 | 0.172 | 0.161 | 0.148 | 0.345 | 0.458 |
| 2.25 | 273 | 0.206 | 0.200 | 0.210 | 0.205 | -0.090 | -0.102 |
| 2.25 | 198 | 0.157 | 0.160 | 0.144 | 0.145 | 0.279 | -0.108 |
| 2.25 | 268 | 0.190 | 0.187 | 0.192 | 0.185 | -0.049 | 0.029 |
| 2.25 | 271 | 0.162 | 0.165 | 0.178 | 0.177 | -0.294 | -0.234 |
| 1.375 | 244 | 0.176 | 0.174 | 0.165 | 0.164 | 0.212 | 0.183 |
| 1.375 | 262 | 0.184 | 0.186 | 0.171 | 0.170 | 0.258 | 0.295 |
| 1.375 | 275 | 0.207 | 0.210 | 0.173 | 0.173 | 0.662 | 0.702 |
| 1.375 | 252 | 0.185 | 0.190 | 0.171 | 0.161 | 0.267 | 0.561 |
| 1.375 | 263 | 0.199 | 0.202 | 0.177 | 0.171 | 0.418 | 0.591 |
| 1.375 | 253 | 0.179 | 0.187 | 0.173 | 0.169 | 0.105 | 0.334 |
| 1.375 | 274 | 0.201 | 0.197 | 0.176 | 0.171 | 0.466 | 0.499 |
| 1.375 | 229 | 0.179 | 0.177 | 0.150 | 0.141 | 0.553 | 0.692 |
| 1.375 | 229 | 0.176 | 0.177 | 0.150 | 0.151 | 0.484 | 0.497 |
| 1.375 | 254 | 0.210 | 0.205 | 0.180 | 0.171 | 0.581 | 0.644 |
| 0.5 | 293 | 0.238 | 0.232 | 0.192 | 0.187 | 0.886 | 0.855 |
| 0.5 | 223 | 0.186 | 0.180 | 0.158 | 0.153 | 0.536 | 0.529 |
| 0.5 | 211 | 0.175 | 0.174 | 0.154 | 0.151 | 0.399 | 0.432 |
| 0.5 | 224 | 0.183 | 0.186 | 0.150 | 0.151 | 0.631 | 0.681 |
| 0.5 | 248 | 0.226 | 0.220 | 0.142 | 0.142 | 1.608 | 1.493 |

| Pallet Gap | Failure Load (lbs.) | Outside Deflection 1 (in.) | Outside Deflection 2 (in.) | Inside Deflection 1 (in.) | Inside Deflection 2 (in.) | Angle 1 (degrees) | Angle 2 (degrees) |
|---|---|---|---|---|---|---|---|
| 0.5 | 240 | 0.206 | 0.195 | 0.143 | 0.138 | 1.192 | 1.088 |
| 0.5 | 246 | 0.193 | 0.188 | 0.157 | 0.156 | 0.686 | 0.597 |
| 0.5 | 254 | 0.219 | 0.219 | 0.155 | 0.160 | 1.208 | 1.141 |
| 0.5 | 242 | 0.177 | 0.172 | 0.159 | 0.159 | 0.342 | 0.263 |
| 0.5 | 261 | 0.189 | 0.189 | 0.161 | 0.162 | 0.532 | 0.522 |
| 0.4375 | 246 | 0.069 | 0.069 | 0.225 | 0.237 | -2.970 | -3.203 |
| 0.4375 | 213 | 0.052 | 0.051 | 0.207 | 0.214 | -2.963 | -3.110 |
| 0.4375 | 207 | 0.062 | 0.061 | 0.198 | 0.209 | -2.607 | -2.838 |
| 0.4375 | 239 | 0.051 | 0.050 | 0.206 | 0.210 | -2.946 | -3.056 |
| 0.4375 | 219 | 0.055 | 0.054 | 0.205 | 0.214 | -2.869 | -3.059 |
| 0.4375 | 255 | 0.056 | 0.057 | 0.220 | 0.233 | -3.123 | -3.360 |
| 0.4375 | 235 | 0.047 | 0.046 | 0.199 | 0.203 | -2.909 | -2.984 |
| 0.4375 | 215 | 0.029 | 0.032 | 0.172 | 0.177 | -2.729 | -2.758 |
| 0.4375 | 214 | 0.047 | 0.046 | 0.200 | 0.202 | -2.935 | -2.963 |
| 0.4375 | 235 | 0.041 | 0.042 | 0.188 | 0.190 | -2.816 | -2.815 |
| 3.0625 | 239 | 0.211 | 0.209 | 0.155 | 0.155 | 1.070 | 1.034 |
| 3.0625 | 241 | 0.203 | 0.199 | 0.188 | 0.181 | 0.293 | 0.336 |
| 3.0625 | 246 | 0.198 | 0.203 | 0.152 | 0.146 | 0.882 | 1.084 |
| 3.0625 | 228 | 0.200 | 0.199 | 0.159 | 0.155 | 0.778 | 0.845 |
| 3.0625 | 239 | 0.211 | 0.209 | 0.155 | 0.155 | 1.070 | 1.034 |
| 3.0625 | 230 | 0.208 | 0.208 | 0.161 | 0.164 | 0.904 | 0.846 |
| 3.0625 | 241 | 0.203 | 0.199 | 0.188 | 0.181 | 0.293 | 0.336 |
| 3.0625 | 246 | 0.198 | 0.203 | 0.152 | 0.146 | 0.882 | 1.084 |
| 3.0625 | 228 | 0.200 | 0.199 | 0.159 | 0.155 | 0.778 | 0.845 |
| 3.0625 | 230 | 0.208 | 0.208 | 0.161 | 0.164 | 0.904 | 0.846 |