Investigation of the Effect of Corrugated Boxes on the Distribution of Compression Stresses on the Top Surface of Wooden Pallets

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Thesis was submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Forestry and Forest Products

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August, 2018

Blacksburg, VA

Keywords: Pallets, Unit Load, Pressure Distribution, Load Bridging, Corrugated Boxes, Packaging.

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ABSTACT (academic)

Pallets are the foundation of unit loads and supply chains. They provide a way to store and transport products in an efficient manner. The load capacity of pallets greatly depends on the type of packages carried by the pallet; however, current pallet design methods do not consider the effect of packages on the load carrying capacity of the pallet. This results in excessive use of materials which reduces the sustainability of unit loads, drives costs up, and creates issues for people in the supply chain. The objective of this study was to investigate the effect of a corrugated box's size and head space on pallet deflection and stress distribution on the top of the pallet as a function of pallet stiffness across multiple pallet support conditions.

Data analysis identified that box size had a significant effect on the deflection of the pallet. This effect was only significant for warehouse racking across the width and length support conditions. As much as a 53% reduction in pallet deflection was observed for high stiffness pallets supporting corrugated boxes with 25.4 mm headspace when the size was increased from small to large. Meanwhile, no significant effect of box size was found for other supports. The effect of headspace was significant in some scenarios but inconsistent thus more investigation with a larger sample size is recommended. In addition, redistribution of vertical compression stresses towards the supports was observed as a function of the increasing box size. The increased concentration of compression stresses on top of the supports and the resulting lower pallet deflection could significantly increase the actual load carrying capacity of some pallet designs.

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Pallets are the foundation of unit loads and supply chains. They provide a way to store and transport products in an efficient manner. The load capacity of pallets greatly depends on the type of packages carried by the pallet; however, current pallet design methods do not consider the effect of packages on the load carrying capacity of the pallet. This results in excessive use of materials which reduces the sustainability of unit loads, drives costs up, and creates issues for people in the supply chain. The objective of this study was to investigate the effect of a corrugated box's size and head space on pallet deflection and stress distribution on the top of the pallet as a function of pallet stiffness across multiple pallet support conditions.

The data from the study identified that box size does have an effect on the deflection of the pallet but, it was only found to be significant for the warehouse racking supports. The highest reduction in pallet deflection was 53% on the high stiffness pallets carrying corrugated boxes with 25.4 mm of headspace as the boxes increased in size. The other support conditions showed no significant effect of the box size. Headspace showed some significant effect in some conditions but was found inconsistent, therefore an investigation with a larger sample size is recommended. In addition, the redistribution of vertical compression stresses towards the supports was observed as a function of increasing box size. This increase in stress on the supports resulted in lower pallet deflection that could significantly increase the actual load carrying capacity of some pallet designs.

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1 Introduction

A wide variety of goods are shipped in the global economy today on a shipping medium known as a pallet. "The pallet is a portable, horizontal, rigid, composite platform used as base for assembling, storing, stacking, handling, and transporting goods" (MH1 2016).They can be manufactured from wood, metal, paper, plastic, and other various composites (Trebilcock 2013). Pallets are the most common foundation used to form a unit load. The usual makeup of a unit load is composed of a wooden pallet, packages made from corrugated paperboard, and plastic stretch wrap that restrains the entire unit load to the pallet. The overall design of the unit load and its components is heavily dependent on the procurement and logistics of each to bring them together.

Two major design methods are used today to design unit loads "Component Based" and Systems-Based." During "Component Based" unit load design, the individual components within a unit load are designed separately without considerations of the other components. This kind of design method does not consider the interaction between unit load components and can lead to overdesign, product damage, or accidents. On the contrary, the "System-based" design methodology, first introduced by Mark White (White 2005), considers the interaction between pallets, packages and material handling systems, thus allowing an optimal use of materials and results in more sustainable and safer unit load designs.

The design of the pallet alone is an essential component to consider, as it acts as the interface for the products between the materials handling equipment. Because when pallets are used in automated warehouses, the deflection of the pallet has a direct effect on the efficiency of the material handling systems. Excessive pallet bending often results in pallet failures and equipment breakdowns. Therefore, the ANSI MH1 standard provides guidelines on the maximum amount of pallet bending that is acceptable for pallets that are intended to be used in automated warehouses. (MH1, 2016)

The structure of the pallets also has a direct effect on the strength of various packaging materials carried by the pallet. The compression strength of corrugated boxes is influenced by the size of the gap between pallet deckboard (Baker, 2016b), overhang of the boxes from the pallet (Ievans, 1975; Monaghan et. al., 1992; DiSalvo 1999;), the stiffness of the pallet deckboards (Baker, 2016b), and the amount of interlocking between palletized boxes (DiSalvo, 1999; Molina, 2017). Yoo et al. (2008) also investigated how the stiffness of the pallet deckboards influences the pressure distribution on the top of the pallet that can have a direct influence on the load capacity of pressure sensitive packaging materials such as pails, bottles, and drums.

The properties of packages carried by the pallet also have a direct influence on the load capacity of the pallet. This interaction between the packages and the pallet is called load bridging that results in pressure redistribution on the top of the pallet that moves more pressure to pallet components that are supported, resulting in less overall deflection of the pallet. The load bridging phenomena was first observed by Fagan in 1982 and Collie in 1984. However, detailed investigation of the factors affecting load bridging did not happen until 2017 when Park et al. conducted preliminary investigations on the effect of box size and strength film containment force using simplified unit load simulator and a warehouse racking support condition. Later Phanthanousy (2017) further investigated the effect of box content using the method developed by Park et al. In 2017, Molina et al. investigated the effect of interlock stacking using full unit loads and multiple support conditions. However, the load bridging phenomena must be further characterized to optimize the design of wood pallets, required investigations of the various factors affecting load bridging and their interactions are required.

2 Objectives

The main objective of this project is to investigate the effect of box size and head space on pallet deflection and compression stress distribution on the top of partial four-way stringer class wooden pallets as a function of pallet stiffness and using commonly pallet support conditions.

3 Literature Review

3.1 Pallets

3.1.1 What is a Pallet?

"Pallets are a material handling base structure that make up one of the three key components to the unit load portion of a product supply chain" (Yoo, 2011). They help facilitate the storage and transportation of goods throughout their production and distribution (Bilbao et al. 2011). The pallets enable goods to be interfaced with, in a bulk manner using various material handling equipment.

3.1.2 History

The palletization of goods has been implemented for over a hundred year (Guzman-Siller 2009). However, the base structure that we know of today as a “pallet” started out as a material handling structure known as a “skid.” Skids are defined as a pallet without any bottom deckboards or bottom deck surface (MH1, 2016). The additions of bottom deckboards in 1925 were essential as they provided additional stiffness, strength, and durability (LeBlanc and Richardson 2003).

Today’s wide spread use of pallet and pallet based containers can be traced back to the United States army decision in 1940 to adopt fork trucks and wooden pallets (Guzman-Siller 2009). They also helped to promote the automation of pallet production to eliminate the shortages that were caused by the low production numbers associated with their handmade assembly. Then after the war, soldiers used their experience with palletization to establish pallet production plants that increased the availability of pallets and the eventual adoption of the pallet by the Grocers Manufacture Association.

3.1.3 Industry at a Glimpse

The pallet industry is segmented in to several different firms that each holds a small amount of the entire market share. However, the majority of this industry is composed of large multinational companies such as Universal Forest Products, Sonoco, ORBIS, and Rehrig Pacific that offer various services within the pallet industry. These larger companies along with smaller competitors offer a pallet product for business’s to purchase and take ownership of, for their supply chain operations. But the ownership of these pallet products can lead to hidden costs, such as repair and complete loss, due to the nature of some open loop supply chains Therefore, the industry has a marketplace need for an alternative solution, a rental pallet. This target market has been pursued by third party pallet management firms that include CHEP a subsidiary of Brambles, Intelligent Global Pooling Systems, (iGPS), and PECO Pallet. (Freedonia 2017). They provide pallets for companies to use, for a fee and they take on the responsibilities of repairs and pallet collection. The pallet demand from these companies can best be split between four different categories food & beverage, construction, general manufacturing, and warehousing/pallet management services.

The wooden pallet accounts for more than 90% of the United States pallet market (Trebilcock 2013) and 508 million new wood pallets were manufactured just in 2017 (Gerber, 2018). Demand for pallets made of other materials exists but are usually considered for, special applications depending on the palletized good. This is because wood preforms well between cost, durability, strength, and ease of manufacturing. However, there are down sides to the use of wood due to its biological nature. It can develop mold and certain species of insects can cause phytosanitary issues. In addition, the fasteners used to hold components together might cause damage to goods if they withdraw from the joint.

The standardization of the pallet industry has vastly changed since its initial implementation improving efficient shipping but due to the specifications of certain industries (Table 1) and the pallet's origin (Table 2), there is still a variety of sizes.

Table 1 Standard pallet sizes found in several industries and their share of annual production per year (Gerber 2018).

Use	Pallet Size (in.)	Share of Annual Production (%)
Grocery	48 x 40	35
Military	40 x 48	4
Chemical	42 x 42	5
Drums	48 x48	7
Chemical, Beverage	48 x 42	3
Automotive	48 x 45	5
Beverage	37 x 37	<1
Beverage, Shingles, Packaged Paper	48 x 36	1
Other Sizes	Various	39

Table 2 Common pallet sizes based on the manufactured country of origin from ISO 6780.

Metric size (mm)	US size (inches)	Region
1200 x 1000	47.24 x 39.37	Europe, Asia
1200 x 800	47.24 x 31.50	Europe
1219 x 1016	48.00 x 40.00	North America
1140 x 1140	44.88 x 44.88	Australia
1100 x 1100	43.30 x 43.30	Asia
1067 x 1067	42.00 x 42.00	North America, Europe, Asia

3.1.4 Classification

The classification of pallet can be broken down into several categories that can help to identify the exact design specifications and their uses. (MH1, 2016) First, the dimensions of the pallet are determined with the length dimension being first followed by the width. The length of the pallet is determined by the direction of the stringers and stringer boards. Stringers and stringer boards are beam components of a pallet that support and space the top and bottom deck boards. Secondly, the overall class is defined by two major classes of pallet: block and stringer.

A stringer pallet is constructed with two or more stringers and multiple deck boards on the top and bottom deck surface of the structure held together by fasteners. In North America, the most common type of stringer pallet is known as a Grocery Manufacture's Association pallet (Clarke 2004). In most cases, stringer pallets are limited to equipment handling in a two-way manner, from the front and back of the pallet. However, more access to equipment can be accomplished by notching a stringer pallet allowing only forklift tines to enter, creating a partial-four way configuration. The notch is an incision that is created in each stringer at the same location so that the forklift's tines can support the pallet across its length. The block style pallet is constructed from multiple wooden blocks that tie the other components, deck boards, and stringer boards together. This design allows for full access from all four sides (four way access) for material handling equipment.

The pallet is then further defined by the pallets planned lifecycle within a supply chain, it could be considered as a single-use or multi-use pallet. Then the matter in which a piece of material handling equipment can enter the pallet is considered. The pallet could be a two-way, partial four-way, or a full four way entry pallet, the type of entry is mostly determined by the first classification.

Pallets also can be classified based on the top and bottom deck construction. Single face pallets only have top decks, while double face pallets have both top and bottom decks. Double face pallets can be reversible when the top and the bottom deck construction are identical or non-reversible when the top and the bottom deck construction are different to accommodate pallet jack handling. The configurations of these top and bottom decks can be further categorized. Top decks can be designed with deck boards, stringer board/deck boards, panels, and panel/stringer boards. Bottom decks can be designed in a unidirectional, overlapping, cruciform, and perimeter fashion. Figure 1 shows an example of for a full pallet classification.

Figure 1 48"x40", Block-Class, Double Face Non-reversible, full four way, stinger board/deckboard top, perimeter base, multiple use pallet.

3.1.5 The Material

Wooden pallets can be created out of softwood lumber, hardwood lumber, and engineered wood products. Solid wood is divided into two species groups: gymnosperm (softwood) and angiosperm (hardwood). Softwood (gymnosperm) trees lack a covering layer on the seeds and hardwood (angiosperm) tress seeds are covered in a fruit. Softwood lumber commonly used in the United States can be found within four families of the order Coniferales, they are Cupressaceae (cedar), Taxaceae (yew), Pinaceae (pine), and Taxodiaceae (cypress) (Hoadley 1980). However, the most abundantly used softwood lumber for pallets can most be found within the family of Pinaceae which includes various species of spruce, pine, larch, and fir. They are typically lightweight, straight grained, and homogeneous in cell structure so the conversion to lumber and building with it is straightforward. The softwood lumber that is purchased for pallet manufacturing is typically kiln dried to a moisture content of 5% to 19%before manufacture.

Hardwood lumber can be separated into the two families of monocots and dicots. The hardwood's cell structure is more densely packed and has a greater variety, leading to higher weights and stiffer material. The most commonly found species to be use for pallets are oak, maple and various mixed hardwoods (Bush and Araman 2009).The hardwood lumber that is used by pallets is typically made from a lower quality, usually the leftover core (cant), due to the high price of hardwood. These cants are moist with leftover water, and in most cases the lumber created from them is still above the fiber saturation point upon pallet assembly.

Engineered wood products such as plywood, oriented strand board, and fiber-based composites are used instead of solid wood only for specific load applications or to simplify manufacturing. For example, many block pallets in the European Union use composite fiber block pallets so they don't have to cut blocks to size in house and help adhere to ISPM 15 Due to the engineered properties of the wood the moisture content is well below the fiber saturation point of 20%..Each of these materials can be utilized to make a wooden pallet, however it should be noted that each source has their own advantages and disadvantages when it comes to sourcing, prices, ease of manufacture, and its moisture.

3.1.6 Pallet Lumber Sizes and Grades

The overall volume of wood used by the pallet industry can be split between 45 percent of hardwood and 55 percent of softwood (Gerber 2018). The hardwood lumber is purchased in large green cants or random lengths of various lumber left over from logs at wood mils. This material is normally classified as NHLA "Below Grade" (NHLA 2015) and doesn't have any particular classification based on its qualities; however grades Common 3A and 3B are used strategically for vulnerable parts of a pallet (Large 1974). Softwood lumber is obtained from nominally dimensioned kiln dried wood. The most common sizes used are nominal 2x4 and nominal 2x6 lumber with random lengths. Softwood lumber for pallet production is typically purchased from lower cost grades of No. 3 common and utility, outlined in the American Softwood Lumber Standard (NIST 2015). Once the lumber and cants from both softwood and hardwood are converted into their respective components they can receive a "Pallet Grade." They can be classified into economy, utility, standard, premium, and select grades (NWPCA 2014). The grades are determined based on the magnitude of multiple lumber defects as listed in Table 3.

Table 3 Lumber characteristics that categorize the grade of the pallet component in Pallet Design System (PDS).

Lumber Characteristic	Pallet Component Grade				
	Select	Premium	Standard	Utility	Economy*
Sound Knots	1/4 of Cross Section Stringer Notch Area: 1/8 of Above Notch Cross Section	1/3 of Cross Section Stringer Notch Area: ¼ of Above Notch Cross Section	1/2 of Cross Section Stringer Notch Area: 1/3 of Above Notch Cross Section	3/4 of Cross Section Stringer Notch Area: ½ of Above Notch Cross Section	7/8 of Cross Section Stringer Notch Area: 5/8 of Above Notch Cross Section
Unsound Knots, Loose Knots, Holes	1/8 of Cross Section	1/4 of Cross Section	1/3 of Cross Section	1/2 of Cross Section	1/2 of Cross Section
Cross Grain	1 in 10	1 in 8	1 in 6	1 in 4	Not Limited
Localized Grain Disorientation	1/4 of Cross Section	1/3 of Cross Section	1/2 of Cross Section	2/3 of Cross Section	Not Limited
Splits, Checks, Shake	1/4 of Part Length	1/3 of Part Length	1/2 of Part Length	3/4 of Part Length	Must not completely separate Component
Wane	1/16 of Cross Section Stringers or Blocks: 1/16 Nail Face x ¼ Height Boards: 1/8 Width x 1/3 Thickness (Any Length)	1/8 of Cross Section Stringers or Blocks: 1/8 Nail Face x 1/3 Height Boards: 1/6 Width x 1/2 Thickness (Any Length)	3/16 of Cross Section Stringers or Blocks: 1/3 Nail Face x 1/3 Height Boards: ¼ Width x 2/3 Thickness (Any Length)	1/4 of Cross Section Stringers or Blocks: 1/2 Nail Face x 1/2 Height Boards: 1/3 Width x Full Thickness (Any Length)	5/16 of Cross Section Stringers or Blocks: 5/8 Nail Face x 2/3 Height Boards: 1/2 Width x Full Thickness (Any Length)
Unsound Wood	None	1/8 of Cross Section	1/4 of Cross Section	1/3 of Cross Section	1/2 of Cross Section
Pith	None	Not Limited	Not Limited	Not Limited	Not Limited
Mismanufacture	None	1/16 of Cross Section	1/8 of Cross Section	3/16 of Cross Section	1/4 of Cross Section

* Economy Component Grade permits lumber characteristics which prevent reliable estimates of strength, stiffness, or durability.

3.1.7 Manufacturing

The manufactures of the pallets using these graded components are well defined in order to provide a uniform product (NWPCA 2014). The leading deckboards must be placed within ±1/4 in. of its designated design location, and all other components must be within ±1/2 in. with exception of the bottom deckboards when there is a stringer notch that can't be covered up by a board. Overall size of the pallet can deviate by ±1/4 inch and -1/2 inch of the desired dimension. In addition, the pallets top and bottom deckboard surface must be within 1/4 inch maximum deviation from corner-to-corner straight line. Finally, the pallet's "squareness" is to be limited to 1.5% or 1 inch difference in the diagonal measurement of the top deck.

The physical assembly of a pallet is typically performed in a manual, semi-automated, or fully automated fashion (Leising 2003). The manual process is typically performed solely by multiple humans with hand tools on a table surface. Semi-automatic production of pallets is performed by an assembly line process that is controlled by a handful of operators as they place components into the machine along the line in a single head machine. For a single head machine the operator needs to place the deckboards into dedicated locations for the design while the machine nailing head nails the deckboards to the stringers. The machine only can work on one face of the pallet at the time, so after nailing the top deckboards the pallet is flipped by the machine and the bottom deckboards are nailed. Fully automated systems are run with computer-aided systems that only require one operator and can attach both faces of the pallet, making it a double head machine. The double head machine, conducts the placement of the boards and the operator only needs to feed new pallet components into the machine. The first head nails the top deckboards to the stringers or stringerboards while the second head nails the bottom deckboards.

3.1.8 Mechanical properties

The mechanical properties of pallets are heavily affected by the components used to assemble the pallet, the wood and fasteners. The wood is a variable material that can determine the strength characteristics of the pallet based on various species-specific properties such as density, microfibril angle, or cell structure and on the amount of characteristics (Table 3). Fasteners make the joint between the wooden components non-linear and semi-rigid affecting the rotation modulus (Wilkinson 1983; Loferski 1985; Samarasinghe 1987; Colclough 1987), the pallet's response to unstable loads, and the overall durability of the pallet.

The prediction of a pallet's mechanical performance through physical testing was originally developed by Fagan (1982) through the development of a testing apparatus and method to apply a uniformly distributed load. The method involved the use of an airbag to simulate the manual loading of pallets with boxes or bags under support conditions commonly found in industry. The methods which is currently included in the ASTM D1185:2017 (Standard Test Methods for Pallets and Related Structures Employed in Materials Handling and Shipping) testing standard provided a way to test pallets in a laboratory setting. Common pallet support conditions include floors support, warehouse rack support, and fork lift support.

For each support conditions, different pallet component are responsible for the overall performance of the pallet (Yoo 2011). During single and multiple floor stacking support, most stress is applied to the top deckboards of the pallet therefore the strength of the top deckboards limits the load capacity of the pallet. (Collie 1984; Loferski 1985). The package on top of the pallet is typically the limiting factor as it compressed by the weight of other packages and unit loads. Meanwhile, during a warehouse racking support condition across the pallet width (racked across the deckboards), the bottom deckboards of the pallet experiences the highest stress thus it limits the load capacity of the pallet. The warehouse racking support condition across the length (racked across the stringers) the stringers of the pallet experience the highest stress but are not typically the limiting support in a supply chain.

3.1.9 Testing and Design

Through years of research, several standard testing methods have been developed by ASTM and ISO. ASTM D-1185:2017 and ISO 8611:2011 (Pallets for materials handling — Flat pallets) testing standards outline test methods to measure the load capacity and durability of the pallet design. The load capacity of the pallet is estimated based on the strength and stiffness of the pallet. The durability of the pallet provides information on the longevity of the pallets design compared to another pallet design. The load capacity of the pallet also dependent on the types of products that the pallet will carry. A maximum working load test outlines in ISO 8611 standard provides information on how to determine the load capacity of the pallet for a specific type of load.

The load capacity and durability of a wood pallet design also can be determined using various computer software packages such as The Pallet Design System (PDS) and Best Pallet. These software can provide an easy and rapid way to design wood pallets without any physical testing. However, due to the lack of research knowledge related to the effect of the different types of load carried by the pallet on the load capacity of the pallet, the software only can provide a safe but conservative estimate of the load capacity of the pallet.

3.2 Corrugated Paperboard Boxes

3.2.1 What is a Corrugated Paperboard Box?

Is a box structure composed of a corrugated paperboard/fiberboard laminate panel made of a fluted paper medium that has one or two more additional sheets of paper (liners) glued to the outside on top of the peaks and troughs of the medium. (Kirwan 2005)

3.2.2 History

The corrugated paperboard that corrugated boxes are composed of has its origins in the mid-19th century. Edward Charles Healey and Edward Ellis Allen patented in 1859 the first corrugated paper to serve as a hat liner in felt hats (Twede and Selke 2005. However, the material wasn't used for packaging until Oliver Long filed for a patent in 1874, which configured the corrugated paper with an additional piece of paper on one side (single face). Robert Gair would purchase Long's patent and later create a combined cut-crease machine to assemble corrugated boxes that made the corrugated box commercially viable. The patent for a "single wall" corrugated board was later filed by Albert Jones however, due to novelty patent law the product was labeled for use in "window shades."

3.2.3 Corrugated Paper and Paperboard Industry

Paper and paperboard packaging is currently the main material used for packaging in the U.S., and is tied with plastics in worldwide usage. Of the different package forms produced from paper and paperboard, the corrugated fiberboard packaging represented a 64% of the total value of the shipments in the year 2011, and a total production for the industry of $26.1 billion in the United States (Twede et al., 2014).

Corrugated boxes are the most common shipping containers made from corrugated fiberboard. The corrugated fiberboard is usually conformed of two outside papers, known as liners, and a corrugated paper in the middle, known as the medium. Different arrangements can be made by changing the medium design (flute) or adding additional layers and combinations of fiberboard in order to adjust the container for each specific use. Corrugated boxes have been for more than a hundred years, the preferred shipping containers for transporting almost every type of goods and currently represent 80% of the volume of shipping materials used in the US (Twede, 2007). The development process began in the second half of the nineteenth century, until reaching a wide usage of the corrugated boxes in the early 1900's, supporting the need for moving the ever increasing amount of consumer goods being manufactured (Twede, 2007).

3.2.4 Corrugated Paperboard Classification

Classification of the corrugated paperboard that compromises a corrugated board box is typically defined by the flute size, flute medium basis weight, and liner board basis weight. The linerboard and flute medium basis weight conveys the fiber content per area (lb. /1000 sq. ft or g/m^2). The fluting medium size is based on the distance between fluting peaks, the number of flutes per unit of length, and the take up factor. The take up factor refers to the length of the flute medium divided by the length of the liner board needed. The most common flute sizes are A, B, C, E, and F.

The use of only one liner and a fluted medium creates a “single face” corrugated board that is often used for cushioning sensitive products. Two liners on both sides of the medium creates a “single wall” product that can be used for a variety of packaging solutions, but is most commonly used for boxes and various inserts. Through the addition of more medium and liner layers a “double wall” and “triple wall” product can be created and are used for heavy duty packaging applications.

3.2.5 The Material

Materials used to manufacture the liner boards are composed of mostly from softwood trees that are rated as pulp wood and is commonly mixed with other recycled paper fibers. In certain, scenarios the need of a completely virgin material is needed for certain applications such as for food and healthcare packaging. The fluted medium is made in a similar process however, the pulp is made from virgin hardwood fiber and recycled fibers. The extra extractives present in hardwood requires the use of a semi-chemical, process in order to separate the fiber and reduce the tearing of the already short hardwood fibers.

3.2.6 Manufacturing

The manufacture of both the liner board and fluted medium both start with the Fourdrinier machine. It is an industrial paper making machine that produces paper in large quantities. The manufacture of the paperboard starts at the “wet end” or the forming section where the fibers are separated from the pulp mixture in the hopper. A wire mesh separates these fibers from the pulp slurry and creates a continuous web of paper. This mat of wet paper is then fed into a series of press rolls that squeezes out as much water as possible and is then sent through another series of heated rollers to remove the remaining moisture. Then the paper is sent through a series of calendar rolls under high pressure to smooth out the surface of the paper and is rolled into a large stock roll.

The correct paper stock with the desired basis weights is then loaded into a corrugator machine that combines and flutes the paper together. The single facer part of the machine then heats up and moistens the paper designated to be the medium, to form the fluted pattern on a set of geared wheels. The fluted medium is then combined with the linerboard on one side with a starch based adhesive to form a single face board. A second linerboard is then attached on the double backer part of the machine to from a single wall corrugated board sheet.

These sheets can then be converted to boxes through the use of die cutting, gluing, and stapling machines. There are two types of die cutting machines typically used in industry; they are the rotary die machine and flatbed die machine. The rotary machine uses a drum and curved die that rotates to cut the sheet, to produce the boxes and other corrugated packages in a rapid manner. The flatbed uses a flat die that must press and retract to produce a box. The box is then constructed through the attachment of adhesives or staples at a manufacture's joints or other design feature.

3.2.7 Mechanical Properties

The mechanical properties of corrugated paperboard are heavily affected by the basis weight, wood fiber quality, flute frequency, and the environmental conditions it experiences. An increase in fiber density, basis weight, results in a stronger paper for all tests according to Kellicut (1959) and Maltenfort (1956). The amplitude and the frequency of the corrugate fluting results in a board with greater bending strength (McKee et. al. 1963). The fiber quality also affects the overall properties heavily, because as fibers are recycled the fiber degrades becoming shorter and shorter resulting in a web of paper with less points of contact with each fiber. The relative humidity of a box's surrounding environment also has a significant effect on the physical properties because it can quickly increase the material's moisture content.

3.2.8 Corrugated Paperboard Box Styles

The regular slotted container (RSC) design is the most used style of box that can be found in packaging today (Twede 2007). This is due to the simple design, ease of manufacture, and the materials savings that equal length top and bottom flaps allow. (Maskell 1986) Other designs are used for more specific applications depending upon the product and the package's end use. Identification and the classification of boxes and their specific styles are done by a four number system created by the European Federation of Corrugated Board Manufacturers (FEFCO) and the European Solid Board Association (ESBO). This FEFCO classification divides corrugated boxes and inserts into nine different categories. For example, the RSC box FEFCO code is 0201 because of its slotted design.

3.2.9 Testing

Standardized testing for corrugated paperboard requires preconditioning before testing due to the effect that ambient relative humidity and ambient temperature have on the board’s moisture content (Maltenfort 1988). The Technical Association of the Pulp and Paper Industry (TAPPI) 402:2013 (Standard conditioning and testing atmospheres for paper, board, pulp hand sheets, and related products), ISO 187:1990 (Paper, board and pulps -Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples), and ASTM 4332:2014 (Standard Practice for Conditioning Containers, Packages, or Packaging Components for Testing) standards state that the board be conditioned at 23°C±1°C at 50.0%±2.0% relative humidity.

The various standardized testing methods used to measure the physical properties of the corrugated paperboard are the edge crush test, flat crush test, bursting strength test, puncture test, and flexural stiffness test. ISO and TAPPI both have their own standardized testing for each of these properties.

The most commonly performed tests to evaluate corrugated board and the box structures made from it are focused on compressive and bursting strength. The compression tests used to evaluate just the board are known as an edge crush test (ECT). There are several different methods used to evaluate it, TAPPI T811:2002 (Edgewise compressive strength of corrugated fiberboard), TAPPI 839:1995 (Edgewise compressive strength of corrugated fiberboard using the clamp method, and ISO 13821:2002 (Corrugated fibreboard-Determination of edgewise crush resistance-Waxed edge method). The ECT value is recognized as an essential factor in the overall strength of a corrugated paperboard box (McKee et al. 1963). In fact, the McKee equation can use the ECT board value to predict the box compressive strength (BCT) using the, corrugated board caliper, and the box’s perimeter. Therefore this value is commonly used by the industry to specify a corrugated board grade (Twede et al., 2014). If the compressive strength of the box needs to be exactly quantified TAPPI 804:2002 (Compression test of fiberboard shipping containers) and ISO 12048:1994 (Complete, filled transport packages) and ASTM D462:2000 (Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads) can be used depending on the required scope of testing.

The burst strength values from the Mullet Burst test act as a metric to evaluate the boxes resistance to general shipping damage (Maltenfort 1988). It tests the corrugated paperboards multidirectional tensile and tear strength in the machine direction, cross direction, and z axis (Twede 2007). The testing standard used to measure this property is TAPPI T808:2001 (Bursting strength of corrugated and solid fiberboard).

3.3 Stretch Wrap

3.3.1 What is Stretch Wrap?

Stretch wrap is a packaging film, which provides a method of containment to help unitize product together and to the top of the pallet. Other methods of containment exist to keep the products such as shrink hoods, polymer strapping, and metal banding but the most common method is stretch wrap (Singh et al., 2014).The film is composed of is typically made from a linear-low density polyethylene resin. The major use of this polymer for stretch wrapping is because of its puncture resistance, inherent elasticity, and its acceptance in the market (Roger, 2011).

3.3.2 Stretch Film Application

Three different methods are used with the industry to apply stretch wrap to a unit load. The manual method of stretch film application requires little to no equipment but requires rigorous labor and results an uneven application of containment force across the unit load's surfaces. Semi-automatic machines apply the stretch wrap automatically and can adjust the amount of containment force, but the unit load needs to be placed in the machine. Fully automatic systems have the unit loads fed into the machine via a conveyor. The stretch wrapping machines are classified by the apparatus that applies the stretch film to unit load. The categories are turntable, straddle, rotary arm, and ring straddle wrapper. These different stretch film applicator designs have different characteristics and are best used for different types of products and operations.

3.3.3 Containment Force Effects

The amount of containment force can affect the overall load stability of a unit load for vibratory and impact scenarios. (Bisha, 2012) In addition, the presence of stretch film coverage from the load to the pallet increases the unit load stability during impacts. The containment force is also proportional to the number of layers applied to a unit load (Singh 2014).

3.3.4 Testing and Methods

The applied containment force of stretch wrap on a unit load can be measured using ASTM D4649:2003 (Selection and Use of Stretch Wrap Films). It measures the containment force only on the flat surface of the unit load and the containment force can't be measured until the film is applied on to the unit load. The effect of the stretch wrap on the load stability of a unit load can be evaluated through the use of ASTM D4169:2009 (Standard Practice for Performance Testing of Shipping Containers and Systems) or ISTA 3E:2009 (Unitized Loads of the Same Product).

3.4 Unit Load Design

3.4.1 Load Bridging Effect on Unit Load Design

The testing of the pallet design for unit loads assumes a uniformly distributed load across the entire pallet and the laboratory testing standard ASTM D1185:2017 uses the same concept. However, the loads that are placed on pallets result in more discrete loading which redistribute the compression stresses toward supported components of the pallet as they deflects. The extent of this phenomenon depends upon the stiffness of the product that composes the unit load. This migration of stress through the product is known as load bridging, see Figure 2.

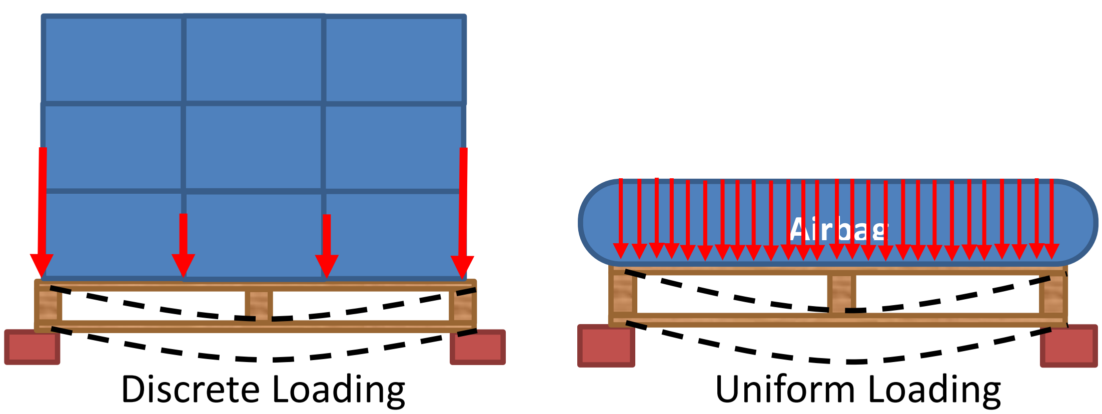

Figure 2 Tributary forces on a pallet represented as line loads on the pallet for the different loading scenarios.

The effect of load bridging was first researched by Fagan (1982) when he investigated pallet performance under four different types of loading. It was found that the load has a significant effect on deflection of the pallet depending on the type of loading and the pallet's stiffness. It was also found that the magnitude of load bridging increased when the pallet stiffness decreases. In 1984, Collie performed additional testing to identify factors that contribute to load bridging using a racking support condition with different load types. His results confirmed Fagan's conclusion that load bridging is significantly affected by the stiffness of the pallet. The racking support across the width was also found to promote load bridging more than the racking across the length support due to the stiffness of the critical component in bending. The different types of load only showed a significant effect on the deflection when low stiffness pallets were used.

The effect of box size on load bridging was noted initially by Collie (1984), as the box size increases the load distributes along less points and more load is redistributed towards the supports. Through the application of beam theory on an elastic foundation Yoo (2011) found that as the pallet stiffness decreases the compression stresses increase near the supports and decrease in the middle of the span resulting in less deflection. The effect of the box size was quantified by Park, (2017) which found up to a 76% reduction in the deflection of a simulated pallet. Finally, Park (2015) also found a load bridging interaction with varying box size and containment force. The applied pressure from the containment force pushed the boxes closer together increasing the load bridging. The stacking pattern of corrugated boxes on a stringer pallet was investigated by Molina in several support conditions (2017). The stacking pattern was found to cause a significant reduction in unit load deflection when the stacking pattern changes from column to any interlocking pattern investigated. This effect was only found to happen in pallet support conditions where deflection is greater, like in warehouse racking for low and medium stiffness pallets.

3.4.2 Design Considerations and Methods for Unit Load Design

The product that a unit load is composed of is an essential design factor to consider before any other component found within a unit load. Products within unit loads can be grouped into three different categories based on their stiffness, strength, and form. (Tanchoco & Agee 1980)

1. Uniform products with a large geometry, made from strong and rigid materials that require little to no packaging to unitize.
2. Irregularly shaped products that require a secondary package to be unitize.
3. Bagged goods that are able to compress into a flat surface.

The load distribution of the pallet will differ for each one of these unit load product categories because of the internal unit load interactions that contribute to load bridging. This phenomenon shows the effect that the product stiffness and its stress distribution have on the pallet. For example, a pallet loaded with a high stiffness product will redistribute its weight, as it deflects, toward the ends of the pallet deck that are supported. In addition, the loading conditions, method of handling, and support conditions for storage must be taken into consideration for the unit load's pallet (Loferski 1985).

The consideration of the factors mentioned above is due to the traditional procedure for the design of unit loads, "Component Based" design. That has historically been handled via individual unit load component designers for the pallet, packaging, and material handling equipment.

"System-Based" design considers how each of these components of a unit load physically interact with other during the storage and distribution of a supply chain. In addition, it brings together the in individual designers in order to create a unit load design that reduces the overall supply chain's operation costs. In addition, it considers a multitude of other unit load component interactions: the vibration and natural resonance of the unit load, stretch wrap containment force load stability, interfacial friction, and product protection. (White 2005)

4 Materials

4.1 Wooden Pallets

A 1,219mm x 1,016mm stringer class, partial 4-way, nonreversible, flush wooden pallet was used for this study. The pallet design was composed of three stringers, five interior top deck boards, two top lead boards, three bottom interior boards, and two bottom lead deck boards, see Figure 51 for drawing of the design. The thickness of the top and bottom deck boards, along with the width of the stringers, were manipulated in order to create low, medium, and high stiffness pallets, see Figure 48, Figure 49, and Figure 50. These stiffness levels were based on the stiffness levels commonly used for wooden pallets (Park 2015). The top and bottom deck boards were constructed from Baltic birch plywood panels of 12.70mm, 15.88mm, and 19.05mm thickness, and the stringers were made from #3 kiln-dried, spruce-pine-fir lumber with no or minimal defects. The dimensions of each of the components are listed in Table 4. Birch plywood was selected for the top and bottom deck boards to ensure consistency and reduce variations that would normally be found in solid lumber due to growth irregularities.

Table 4 Dimensions and quantities of pallet components used to assemble low, medium, and high stiffness pallets.

		Low Stiffness Pallet	Medium Stiffness Pallet	High Stiffness Pallet
Top and Bottom Lead Deckboard	Quantity	4	4	4
	Length (mm)	1016	1016	1016
	Width (mm)	140	140	140
	Thickness (mm)	12.70	15.88	19.05
Top and Bottom Interior Deckboard	Quantity	8	8	8
	Length (mm)	1016	1016	1016
	Width (mm)	102	102	102
	Thickness (mm)	12.70	15.88	19.05
Notched Stringers	Quantity	3	3	3
	Length (mm)	1016	1016	1016
	Width (mm)	88.9	88.9	88.9
	Thickness (mm)	12.70	15.88	19.05

The Modulus of Elasticity (MOE) of all components was calculated using Equation 1 for the solid wood components and for the plywood components. The load deflection curve required for the MOE calculation was obtained pre-assembly through a three-point bending method utilizing a MTS (Model Number 322.31) universal testing machine equipped with a 5500 lbf. (0.26 MPa) load cell (Model Number 661.2DE.01). The deflection of the components were measured at the center of the span using a Schaevitz (Model Number 2000HRDC) linear variable displacement transducer (LVDT) secured to wooden yokes. The MOE of the components made from Baltic birch plywood (91.44 cm bending span) were measured according to the methods specified in ASTM D3043 (2015). The MOE of the components made from solid lumber according to the methods in (111.76 cm bending span) ASTM D198 (2015).

Equation 1 Modulus of Elasticity calculation use for the wood components.

$$Modulus\ of\ Elasticity\ (MOE) = \frac{Pl^3}{4bd^3\Delta}$$

$$P = Load\ (pascal)$$
$$L = length\ (meter)$$
$$b = thickness\ (meter)$$
$$d = height\ (meter)$$
$$\Delta = change\ in\ deflection\ (meter)$$

All plywood and solid lumber samples had a pilot hole drilled in the neutral axis and 5.08cm away from each end near the pivot point in order to place a screw at those locations to support the LVDT and its yoke. All samples were tested in a flatwise orientation. The loading rates for the birch plywood components were based on the changing dimensions of thickness and width while the stringers used consistent loading rates as recommended by ASTM D198 (2015). The supports and load applicator were all constructed following the recommendations of ASTM D198:2015 and ASTM D3043:2015. The results are presented in Table 5. The MOE data collected for each of the pallet components was used in order to sort the boards into different stiffness levels.

Table 5 Average Modulus of Elasticity values of pallet components for each stiffness design.

		Low Stiffness Pallet	Medium Stiffness Pallet	High Stiffness Pallet
Top and Bottom Lead Deckboard	Average MOE, (MPa)	9849	8922	9150
	COV (%)	4	3	4
Top and Bottom Interior Deckboard	Average MOE, (MPa)	9033	8699	9002
	COV (%)	4	3	5
Stringer	Average MOE, (MPa)	10080	8141	9998
	COV (%)	15	13	11

The pallet components were assembled together using (Fastenal #8 3.81 and 4.13cm bugle head, plain finish, Philips drive) screws. Screws were selected, in order to ensure that the connection between the components stay rigid. The holes left from the assembly were filled in with wood putty in order to ensure a smooth surface for the pressure mat which picks up even the smallest difference in surface quality. Overall, the bending stiffness of the pallets was measured using ASTM D1185:2017. A Tinius Olsen compression tester with an air bag was used to apply a uniform load. The support conditions for the bending stiffness measurements replicated the support conditions used for the actual experiment. The pallets' stiffness levels are listed in Table 6. The pallets' stiffness levels in the racking condition were evaluated to understand the combined effect of the components and to provide a baseline for the deflection to be expected as compared to the Pallet Design System™ (PDS) values.

Table 6 Average pallet stiffness for the low, medium, and high stiffness pallet designs under uniform loading in various supports.

	Pallet Stiffness (N/m)		
	Low Stiffness	Medium Stiffness	High Stiffness
Pallet Bending - Racked Across Width	256	428	601
Pallet Bending - Racked Across Length	714	828	910

4.2 Corrugated boxes

Three different sizes of corrugated boxes were investigated. The outside dimensions were 50.48cm x 40.48cm x 30.48cm (large boxes), 40.48cm x 32.86cm x 30.48cm (medium boxes), and 29.85cm x 25.24cm x 30.48cm (small boxes). Inside dimensions for the boxes were 49.69cm x 39.53cm x 28.598cm (large boxes), 39.53cm x 31.91cm x 28.58cm (medium boxes), and 29.37cm x 24.29cm 28.58cm (small boxes). The boxes were production grade, right-handed, regular, slotted container (RSC) style boxes. The boxes were made of a nominal 7.71 N/mm ECT rated, C-flute, corrugated board. The boxes were manufactured by the Packaging Corporation of America in Roanoke, Virginia. They were shipped flat with the industry standard manufacturer's joint already glued. The physical properties of the corrugated board were measured using the guidelines of the applicable ISO and TAPPI standards. The summary of the physical properties of the investigated corrugated board are listed in Table 7.

Table 7 Physical properties of the corrugated board used for the investigated corrugated boxes.

Testing Characteristic	Standard	Average Value	COV (%)
Edgewise Compressive Strength	TAPPI T 811 (2007)	8.95 N/mm	20.15
Bending Stiffness Machine Direction Outside	ISO 5658 (2006)	29.7 N/mm	9.4
Bending Stiffness Machine Direction Inside	ISO 5658 (2006)	29.4 N/mm	2.9
Bending Stiffness Cross Direction Outside	ISO 5658 (2006)	8.2 N/mm	6.6
Bending Stiffness Cross Direction Inside	ISO 5658 (2006)	9.39 N/mm	5.1

The bottom flaps of the corrugated box were secured using 3M Scotch-Weld Hot-Melt #3762. Three parallel beads of glue were applied to the minor flaps and then the major flaps were brought together. A 90° jig was used to ensure that all box walls were square with each other as they were glued. Standard packaging tape was added to the edges of the top major flaps in order to reduce fiber tearing when the box interior was accessed during the study. Wooden blocks and plywood pieces were used to fill the corrugated boxes for weight. The wooden blocks and plywood pieces were placed into the boxes in an upright orientation leaving approximately 2.54cm headspace. When the boxes were to be tested without headspace, a 2.44cm piece of insulation foam was cut to size to fill the headspace. The weight of the foam pieces was negligible. The average weights of the small, medium, and large boxes were 10 kg, 18.1 kg, and 27.2 kg, respectively.

4.3 Unit Load

To form layers, sixteen small boxes (in a 4x4 pattern), nine medium boxes (in a 3x3 pattern), or six large boxes (in a 2x3 pattern) were used (Figure 3). The stacking patterns and box sizes resulted in an underhang around the perimeter of the pallet measuring between 0.08 cm to 1.51 cm. Two unit loads were assembled with each box size to investigate the pressure distribution between the two unit loads during double stacking. To form the bottom unit load, four layers of corrugated boxes were stacked on the pallet in a column stack pattern (Figure 3). To form the second unit load, two layers of corrugated boxes were stacked on the pallet in a column stack pattern. The palletized boxes were then secured using an eighty micron thick, low-density polyethylene stretch film (manufactured by Uline). A semi-automatic Wulftec machine (Model Number WSML-150-b) was used to apply the stretch film to the unit load on the pallet. The machine settings included a 200% pre-stretch with three bottom layers and three top layers all with a 40% overlap. The applied containment force of 5.4 kg was measured using a Highlight Film Force Pull Kit (PTC-919) and scale and followed the procedure outlined in ASTM D4649 (2016). This represents the low end of commonly applied containment forces for this type of unit load. This is the force that safely keeps the boxes in their stacked pattern while the unit load is handled by forklifts. To simulate double stacking, a 7.62cm thick polypropylene foam pad (138.43cm x 121.92cm) and a 1.27cm thick sheet of plywood (121.92cm x 109.22cm) was placed on the top of the second unit load. A dummy unit load weighing 435.45kg was placed on top of the plywood to (Figure 4).

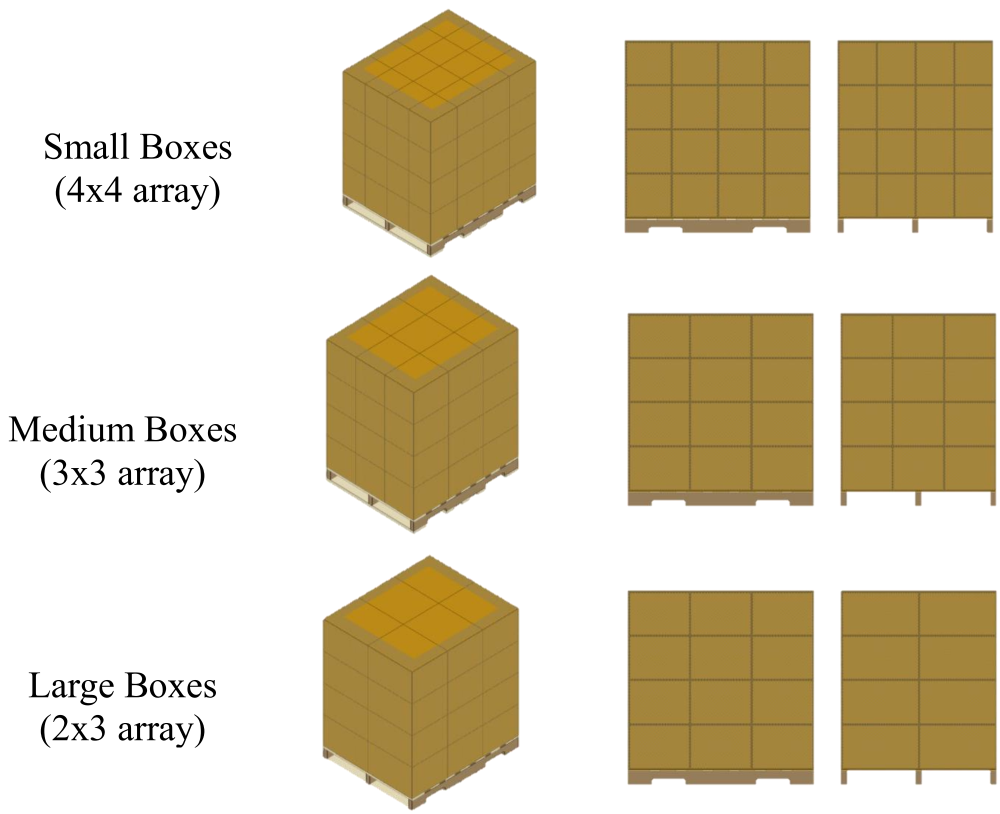

Figure 3 Isometric and side views for the column stacking pattern for unit loads containing small, medium and large boxes.

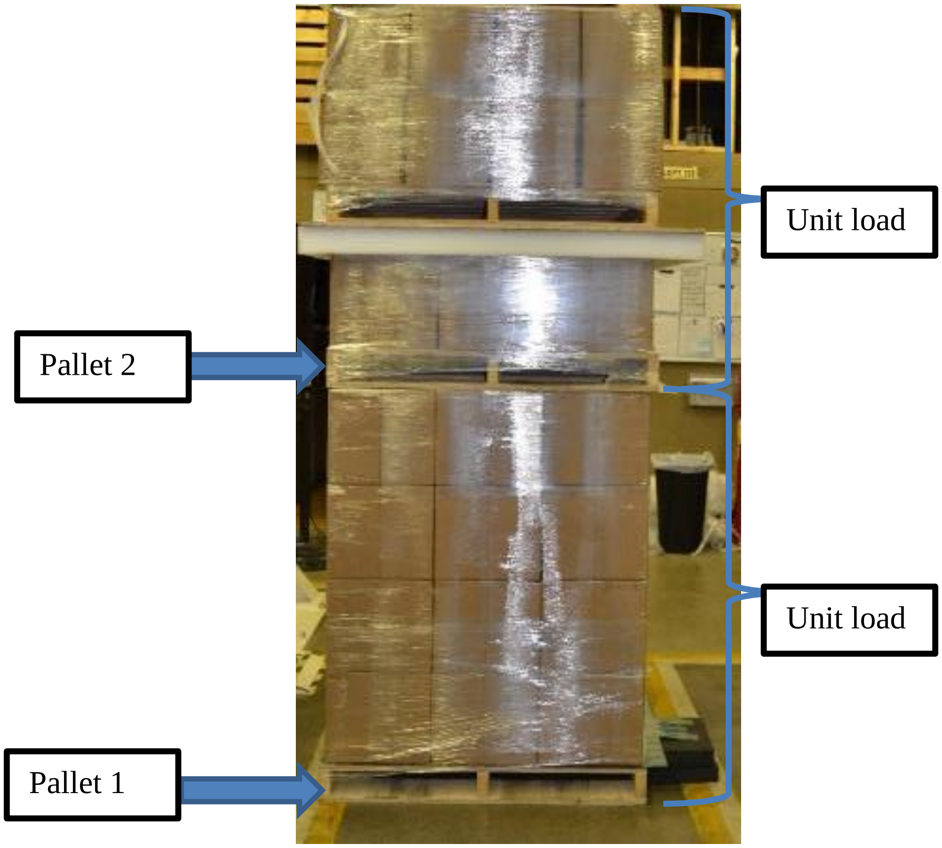

Figure 4 Representative picture of the double stacked support condition.

5 Methods

5.1 Pressure Measurement

A VersaTek™ pressure measurement system from TekScan™ equipped with I-Scan® software was used to capture the pressure interactions between the boxes and the pallet. The model numbers of the pressure mats used for this research were 7200N and 7202N. The 7200N has a pressure mat sensitivity range of 20.68KPa to 2068KPa, and the 7202N has a range of 20.68KPa to 689KPa. The mat sensors cover an area of 70.4cm x 62.6cm which contains individual sensels (sensor cell size 0.51cm^2) spaced 0.711cm apart, resulting in a total of 99 rows and 88 columns.

The entire system was connected to a universal power supply in order to cancel out any electrical noise that could affect the pressure readings. The handles that were connected to the pressure mat were also grounded through a grounding wire. The wire was attached to the I-beams during racking supports, the back reset during fork tine support, and any nearby metal during floor support. Also, the mats were encased in two 0.6985mm thick PET plastic sheets in order to ensure the durability of the mat throughout testing. Figure 5 shows the mat inside the protective sleeve.

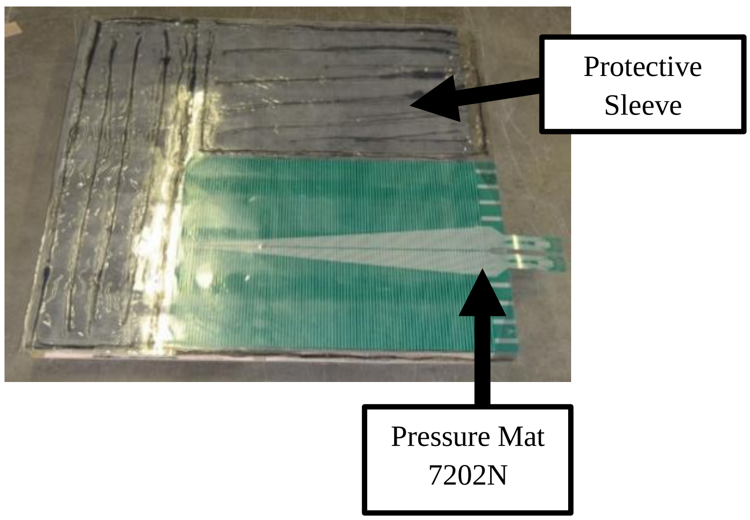

Figure 5 Representative picture of the 7202N series pressure mat inside its protective sleeve covering a quarter of the top deck of a test pallet.

A rubber mat was placed on the top and aligned with the edges of the pallet used for the bottom unit load then the 7202N series pressure mat inside of its protective sleeve was placed on top of the rubber mat. The rubber mat was used in order to reduce any pinching or bending of the pressure mat between the pallet's deck board gaps. The pressure mat was set to a sensitivity setting of S-34 for all testing in the companion I-Scan® software The first row of sensors was aligned with the front right edge of the pallet to ensure that the same area is captured each time. Boxes were then stacked on the pressure mat and the unit load was stretch wrapped. The 7200 series pressure mat, in its case, was placed on top of the first unit load (Figure 6). A snapshot of data from 7202N was taken in every support condition during the six-part cycle right after the deflection measurements were taken. The investigated unit load was moved between the different support conditions in the following order: warehouse racking across the width, fork tine support across the width, warehouse racking across the length, fork tine support across the length, floor support, and double stacked floor support (Figure 7). The snapshots are a visual representation of tabulated data from each of the sensels on the pressure mat. The 7200 model was used to measure the pressure distribution for the double stack condition only.

Figure 6 Placement of pressure mats on unit loads during the testing cycle.

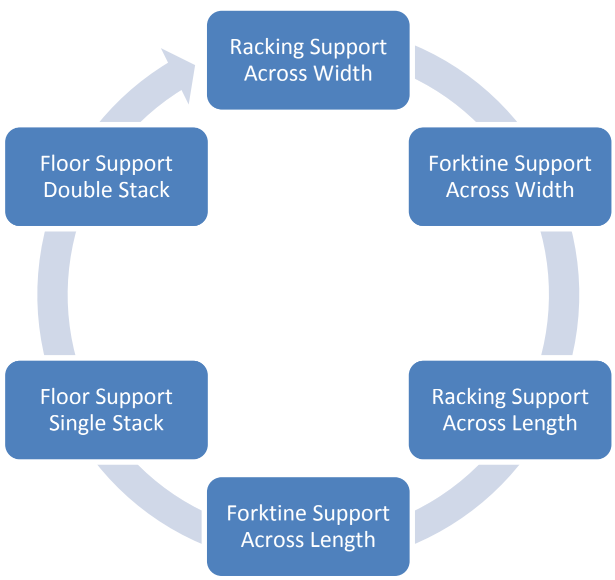

Figure 7 The order of the supports tested within one cycle of this testing method.

5.2 Pallet and pallet component deflection test

Performance of the pallet in these six different support conditions during the study was observed. Zero reference measurements were taken on the pallet used for the bottom unit load before every testing cycle. On the pallet used for the second unit load, zero reference measurements only needed to be taken on the bottom deckboards. Once all of the zero measurements were completed, each unit load was stacked with the appropriate boxes and stretch wrapped before any tests began. To ensure that the pallet is flat, 22.68kg weights were placed on the pallet prior to reference deflection measurements being taken for the warehouse racking and fork tine support conditions. The weights were positioned directly above the supports for each condition to ensure that they did not cause any additional deflection of the pallet. The zero reference measurements were taken using the techniques presented for each support condition in 5.2.1, 5.2.2, 5.2.3, and 5.2,4.

5.2.1 Floor Stacking Support Condition

During the floor support condition single stack condition, the pallet was loaded with four layers of corrugated boxes and was placed on a level floor within the laboratory. The floor support double stack condition was performed by placing and centering a second unit load on top of the first unit load (Figure 8).

The locations of the deflection measurements are presented in Figure 9. The deflection of the selected top and bottom deck boards were measured using a custom jig utilizing a Mitutoyo (2416 S) mechanical dial gauge (Figure 10) with a range of 0.508±0.0.001 cm. The deflection at each location was measured three times, two minutes after the forklift stopped manipulating the pallet interfaces.

Figure 8 Floor support condition setups for single and double stack unit loads.

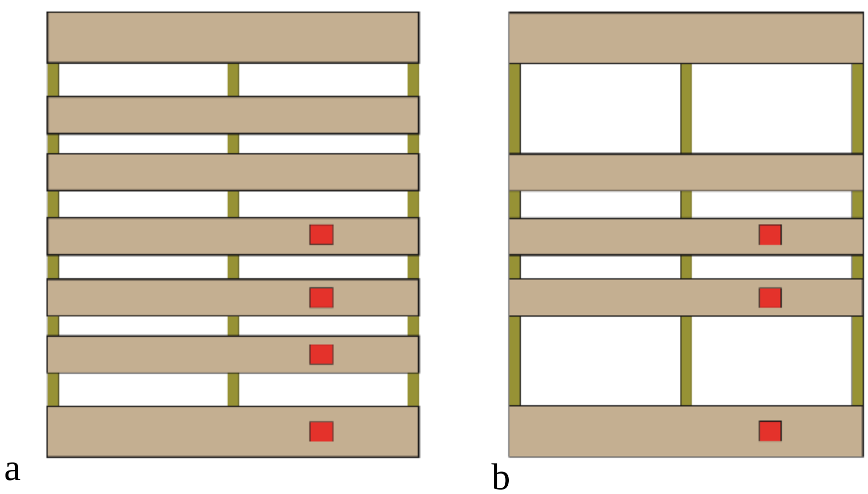

Figure 9 Locations of the deflection measurements of the (a) top deckboard of the bottom unit load and the (b) bottom deckboard of the second unit load.

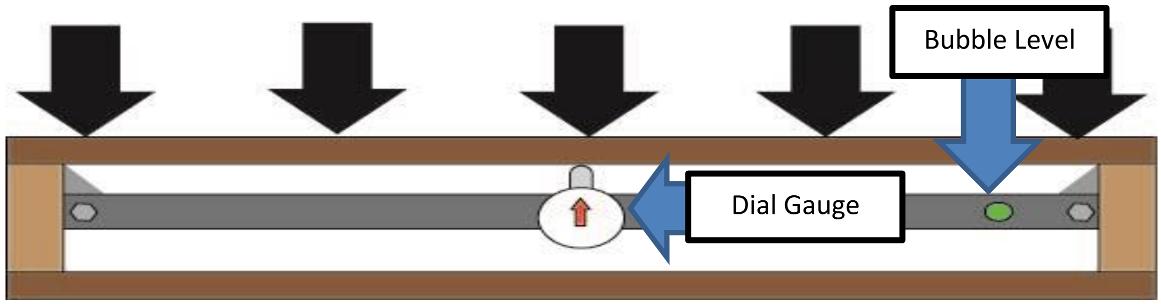

Figure 10 Adjustable deckboard deflection jig created with angled aluminum stock, bubble levels, and a Mitutoyo (4216 S) mechanical dial gauge.

5.2.2 Fork tine support

During the fork tine supports condition, the pallet was supported on two 10.16cm wide and 152.4cm long fork tines. The fork tines supported the entire length of the pallet. The outside-to-outside span between the fork tines was 570mm for the fork tine support across the width condition, and it was 690mm for the fork tine support across the length condition. The unit load was centered on the fork tines which had been leveled prior to testing. These setups are shown in Figure 11 and Figure 12.

The deflections at the four corners of the pallet were measured. Measurements were obtained using a custom jig that rested on the fork tines as a stable reference point. Two different jigs were used to take the measurements of the different fork tine spans (Figure 11 and Figure 12). The jig used for the fork tine support across the length condition used two Starrett (Model 25-441) with a 5.08±0.003cm range. The jig used for the fork tine support across the width condition used two Mitutoyo Digimatic Indicators (Model ID-S1012E) with 1.27±0.002cm range.

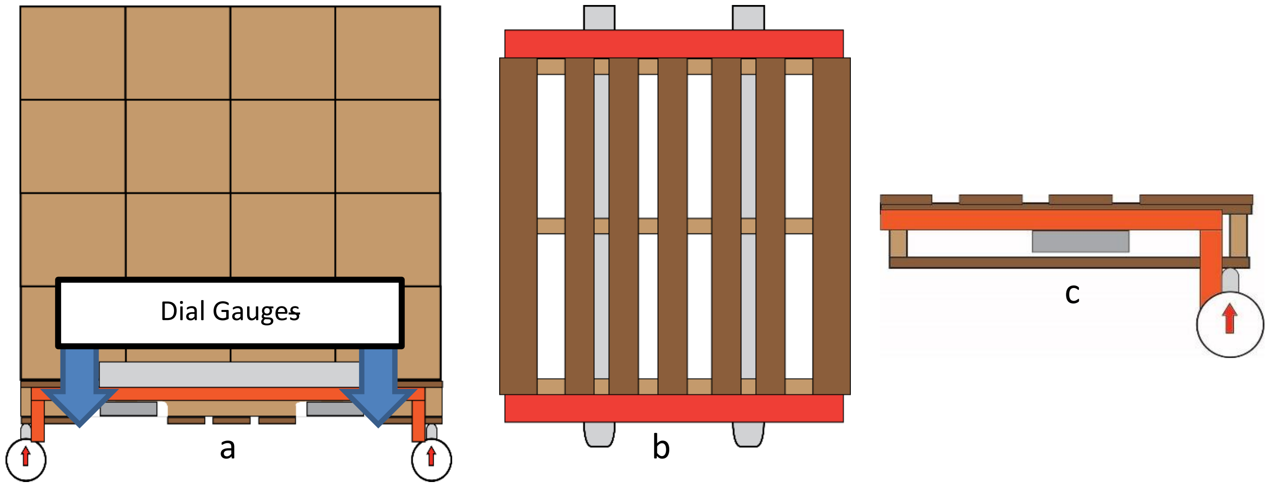

Figure 11 Location of the custom jig and deflection measurements for fork tine support across the length: (a) full unit load view (b) pallet top view and (c) front detail view.

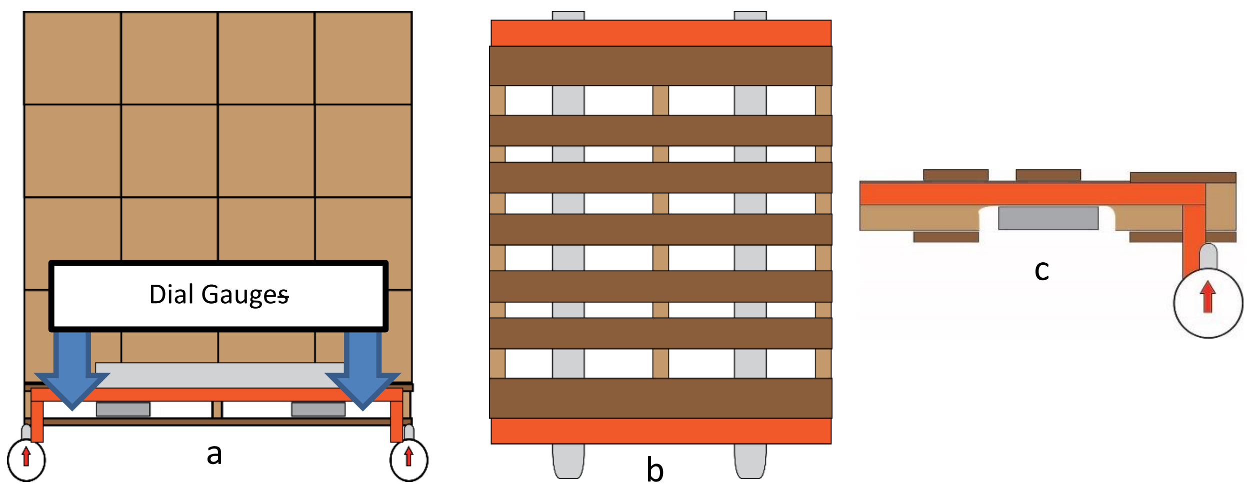

Figure 12 Location of the custom jig and deflection measurements for fork tine support across the width: (a) full unit load view (b) pallet top view and (b) front detail view.

5.2.3 Racking Support across the Length Support

During the warehouse racking across the length support condition, the loaded pallet was supported on two 5.08cm x 5.08cm x 152.40cm solid steel beams spaced 111.76cm apart. The size of the support beams and the span between the beams both followed the guidelines of ASTM D1185 (2017). The stringers of the pallet were perpendicular to the support beams. Prior to testing, the entire unit load was centered on the rack using a forklift (Figure 13).

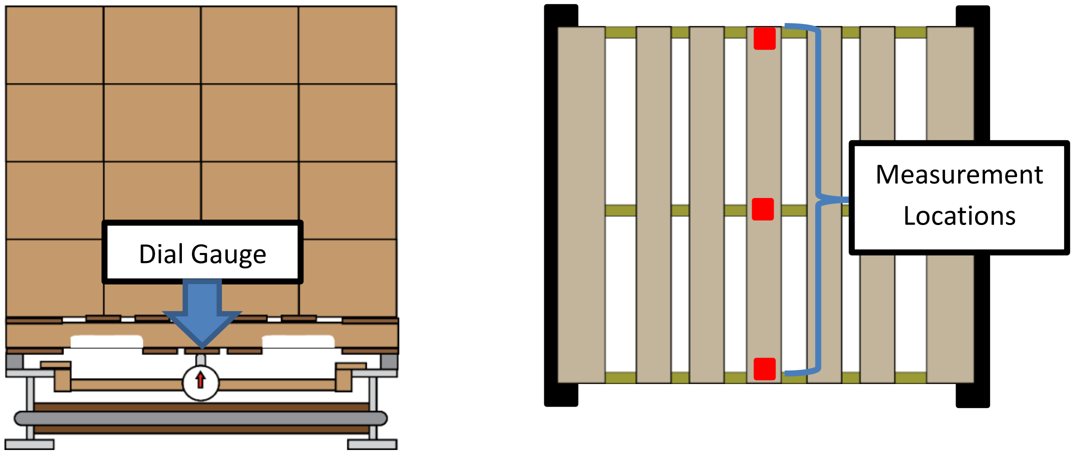

Figure 13 Experimental setup for the warehouse racking support condition across the length of the pallet and the deflection measurement locations.

The deflection of the unit load was measured in three locations; two minutes after the forklift stopped manipulating the pallet interface (Figure 13). Deflections were measured using a Mitutoyo Digimatic Indicator (Model C1050CEXB) with a 5.72±0.004cm range fastened to a custom yoke that was supported on the I-beam flanges.

5.2.4 Racking Support across the Width Support

During the warehouse racking across the width support condition, the loaded pallet was supported on two 5.08cm x 5.08cm x 152.40cm solid steel beams spaced 91.44cm apart. The size of the support beams and the span between the beams both followed the guidelines of ASTM D1185:2017. The stringers of the pallet were perpendicular to the support beams. Prior to testing, the entire unit load was centered on the rack using a forklift (Figure 14).

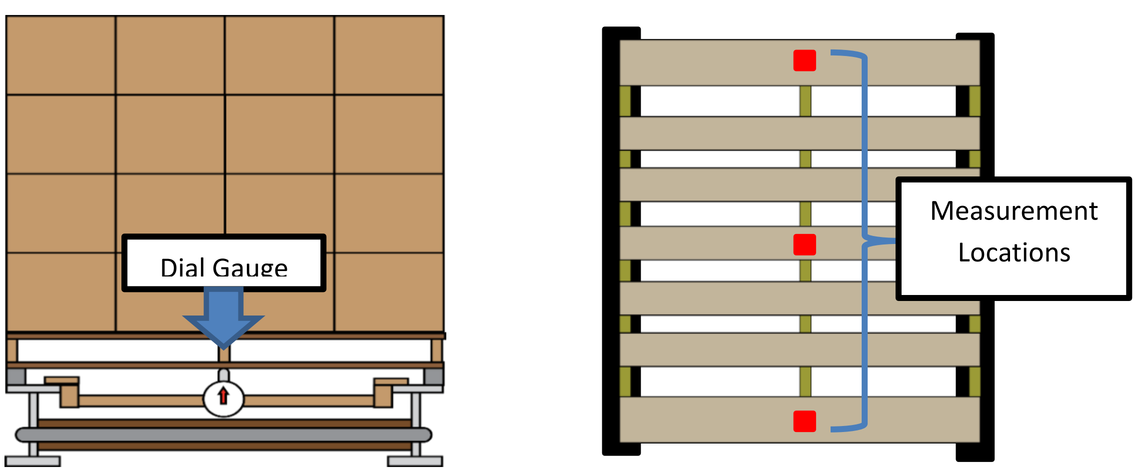

Figure 14 Racked across the width measuring positions and the location of the dial gauge.

The deflection of the unit load was measured at three locations; two minutes after the forklift had stopped manipulating the pallet interface (Figure 14). Deflections were measured using a Mitutoyo Digimatic Indicator (Model C1050CEXB) with a 5.72± 0.004cm range fastened to a custom yoke that was supported on the I-beam flanges.

5.3 Experimental design

The experimental design for this study was an eighteen one-way factorial experiment with one independent categorical variable (box size) with three levels. The treatment conditions were repeated three times to evaluate the treatments under different support conditions, box size, box headspace conditions, and pallet designs. The experimental design was run individually for the different box sizes (small, medium large) and the box headspace condition (no headspace or 2.54 cm of headspace). Every test cycle followed the order laid out in Figure 7. Table 8 shows the experimental designs as they were performed. The deflections of different headspace conditions with the same size box and pallet stiffness treatments were compared to each other using two sample T-tests.

Table 8 The experimental design used in the research.

Pallet Design	Box Head Space	Package Outside Dimension	Number of Cycles
Low Stiffness	0 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3
	2.54 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3
Medium Stiffness	0 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3
	2.54 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3
High Stiffness	0 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3
	2.54 cm	50.80 cm x 40.64 cm x 30.48 cm	3
		40.64 cm x 33.86 cm x 30.48 cm	3
		30.48 cm x 25.40 cm x 30.48 cm	3

5.4 Statistical Analysis

The statistical analysis methods that were used on the data from this study were the Tukey's HSD test and a pairwise T-test. A one-way analysis of variance was performed along with a multiple comparison post-hoc analysis through the use of Tukey's Honest Significant Difference at alpha 0.05 level to find any differences in the pallet deflection values measured for the different packages sizes as a function of pallet stiffness and head space. A pairwise T-test using alpha 0.05 level was used to analyze the headspace and no headspace data between each box size on each different pallet stiffness level. In addition, power calculations were used to evaluate the possibility of incorrectly rejecting the null hypothesis.

5.5 Assumptions

In these methods, several assumptions had to be made in order to control several variables within the experimental setups.

- The containment force used for the study was selected to represent the lowest containment force value that is commonly used for unit loads similar to the ones tested in this research. After an interview with a stretch wrapping equipment manufacturer, a range of 5.44 to 6.80kg containment force was recommended based on our unit loads weight. Therefore, 5.44kg containment force was selected for this research.
- The box height and number of layers was chosen based on the efficient use of trailer space for shipping and warehousing. A common practice is to restrict the height of the unit load to 50in, including the height of the pallet, to allow double stacking in a trailer.
- The pallet stiffness levels were changed by changing the height of the deckboards and width of the stringer boards.
- The screw fasteners were selected to secure the pallet components together to avoid any loosening of the connections after repeated testing.
- The weight of the unit load, 653.17kg, was also assumed by using the average load typically on to a pallet, which is 635.03 to 725.29kg.The column stacking pattern was used for this study to keep the weight of the boxes evenly distributed at the corners, the strongest point of a box.
- The friction between each of the boxes if fixed due to the corrugated boxes being created from the same corrugated board.

- The fill content of the boxes used a granulated load for ease of weight transfer between box size variables; according to Phanthanousy (2017) the fill content will not affect the weight distribution.

6 Results and Discussion

6.1 Racked Support Across the Width Deflections

The deflection of pallets measured during testing for the racking support across the width condition were divided for data analysis in order to separately present a center point and end points for the deflection of the pallet. The two end deflections were averaged for each test replicate in order to compare the data to previous research on pallet deflection (Fagan 1982). In addition, the data for the different box sizes, conditions (headspace/no headspace), and stiffness treatments were additionally separated for statistical comparison. Table 9, Table 10, Figure 15, and Figure 16 shows the deflection measurements at the center of the pallet for racked across the width support condition; meanwhile, Table 12 and Table 13 show the average deflection at the end points of the pallet. For statistical analysis, Table 11 and Table 14 show a 2-sample T-test comparing the deflections of the pallets based on the box conditions of headspace and no headspace.

Table 9 Summary table of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the width using boxes with no headspace and the decrease in deflection compared to the small box size.

BOX SIZE	**AVERAGE PALLET DEFLECTION (MM)**					
	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	11.04(0.69) A		8.24(0.41) A		6.27(0.90) A	
MEDIUM	10.09(0.23) A	8.61%	7.34(0.29) A	10.92%	5.23(0.07) A	16.59%
LARGE	6.64(0.08) B	39.86	5.00(0.62) B	39.32%	3.19(0.43) B	49.12%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 10 Summary table of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the width using 25.4 mm of headspace and the decrease in deflection compared to the small box size.

BOX SIZE	AVERAGE PALLTE DEFLECTION (MM) Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	11.00(0.40) A		7.87(0.43) A		6.78(0.64) A	
MEDIUM	9.00(0.10) B	18.18%	6.89(0.43) A	12.45%	5.67(0.41) A	16.37%
LARGE	6.96(1.02) C	36.72%	5.21(0.83) B	33.79%	3.19(0.43) B	52.95%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 11 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the center data deflections from no headspace and 25.4 mm headspace boxes during warehouse racking support across the width.

BOX SIZE	LOW STIFFNESS PALLET		MEDIUM STIFFNESS PALLET		HIGH STIFFNESS PALLET	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL	0.15	0.89	1.65	0.24	-0.63	0.59
MEDIUM	9.26	0.01*	5.26	0.03*	-1.60	0.25
LARGE	-0.51	0.66	-0.36	0.76	0.00	1.00

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 samples T-test comparison.
* = Variable that rejects the null hypothesis.

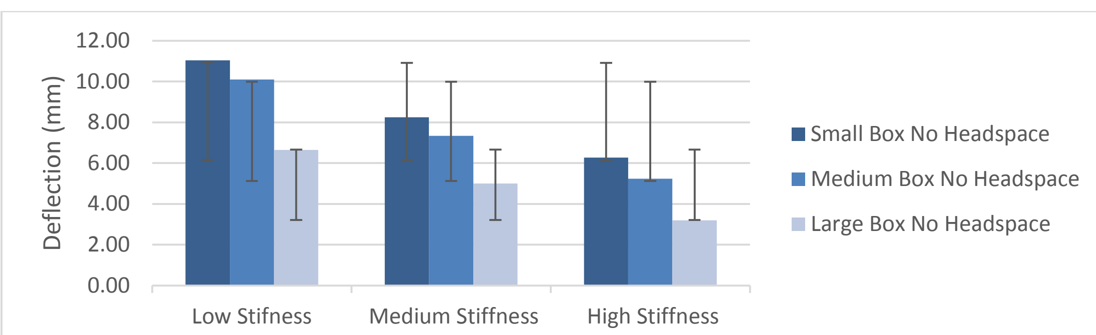

Figure 15 Graph of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the width for boxes with no headspace. The bars represent standard deviation.

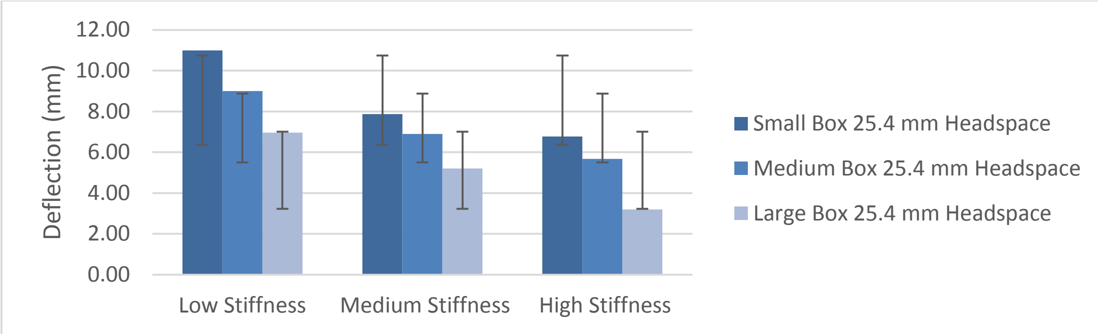

Figure 16 Graph of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the width for boxes with 25.4 mm. headspace. The bars represent standard deviation.

Table 12 Summary table of the average pallet deflection measured at the ends of the pallet during the warehouse racking support across the width using boxes with no headspace and the decrease in deflection compared to the small box size.

BOX SIZE	AVERAGE PALLET DEFLECTION (MM)					
	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	10.54(0.83) A		7.70(0.52) A		5.72(0.83) A	
MEDIUM	9.57(0.37) B	9.20%	6.76(0.49) B	12.21%	5.04(0.47) A	11.89%
LARGE	6.37(0.28) C	39.56 %	4.61(0.80) C	40.13%	3.30(0.51) B	42.31%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05

Table 13 Summary table of the average pallet deflection measured at the ends of the pallet during the warehouse racking support across the width 25.4 mm of headspace and the decrease in deflection compared to the small box size.

BOX SIZE	AVERAGE PALLET DEFLECTION (MM)					
	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	10.52(0.72) A		7.62(0.51) A		6.69(0.80) A	
MEDIUM	8.64(0.43) B	17.87%	6.52(0.61) A	14.43%	5.45(0.47) B	18.54%
LARGE	6.74(1.21) C	35.93%	4.90(1.07) B	35.69%	3.32(0.51) C	50.37%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05

Table 14 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the ends data deflections from no headspace and 25.4 mm headspace boxes during warehouse racking support across the width.

BOX SIZE	**LOW STIFFNESS PALLET**		**MEDIUM STIFFNESS PALLET**		**HIGH STIFFNESS PALLET**	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL	0.06	0.96	-0.28	0.78	2.07	0.07
MEDIUM	3.98	0.003*	0.75	0.47	-1.53	0.16
LARGE	0.73	0.50	0.53	0.61	-0.06	0.95

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

Change in box size had a significant effect on center point pallet deflection for all of the pallet stiffness levels (low 373,545 N/m; medium 664,080 N/m; high 931,449 N/m) and headspace conditions using the racking support across the width. The end deflections also showed that change in box size has a significant effect on deflection for all stiffness levels; although, the ends deflected less than the center deflections. These trends align with previous studies Collie, 1984; Fagan, 1982; Park et al., 2017). The high stiffness pallet showed the largest reduction in center deflection (53%) when the size of the corrugated box was increased from small (30.48cm x 25.40cm x 30.48cm) to large (50.80cm x 40.64cm x 30.48cm) for boxes with 25.4mm headspace.

The box headspace conditions investigated showed that, for most treatments, no statistical difference could be found between them except for medium boxes (40.48cm x 32.86cm x 30.48cm) on low and medium stiffness pallets. However, the greatest significant difference in between the deflection of the pallet using boxes with and without headspace was only 9.3%.

6.1.1 Racked Support Across the Width Pressure Readings

The distribution of pressure on the top surface of the pallet was recorded using a 7202N TekScan™ pressure mat. The following figures demonstrate how all pressure mat data was analyzed to observe the compressive forces on the pallet.

Figure 17 shows the pressure distribution outputs on a low stiffness pallet in a warehouse racking support across the width condition with various box variables. To visualize pressure distribution across the pallet, the data from the pressure sensels are presented in Figure 18 to Figure 23. These figures are created by summing all of the sensels rows or columns that are parallel to the supports. The values of these summed sensels are then plotted across the span of the support condition. In each of these figures, a graphical representation is included; they show the location of pallet components and boxes in relation to the peaks of the summed sensels.

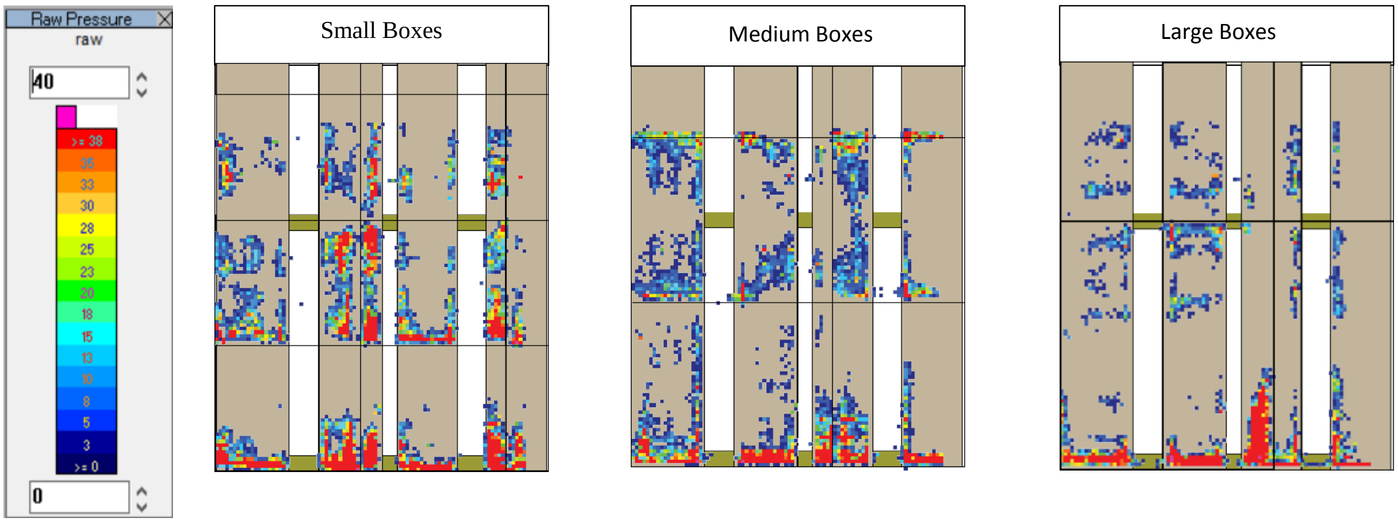

Figure 17 Pressure distribution example on the top surface of the pallet during warehouse racking support across the width for 25.4 mm headspace scenarios using different box sizes on the lowest stiffness pallet. The legend to the left indicates value for the colors that are obtained from the TekScan™ pressure mat.

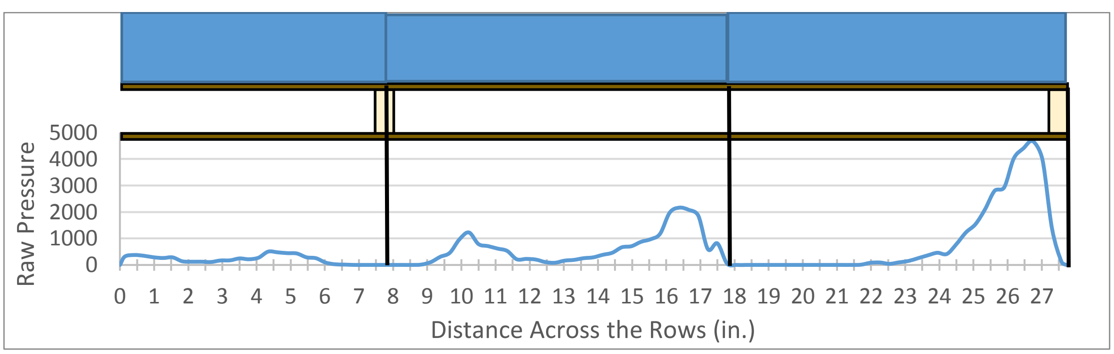

Figure 18 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using small boxes with no headspace.

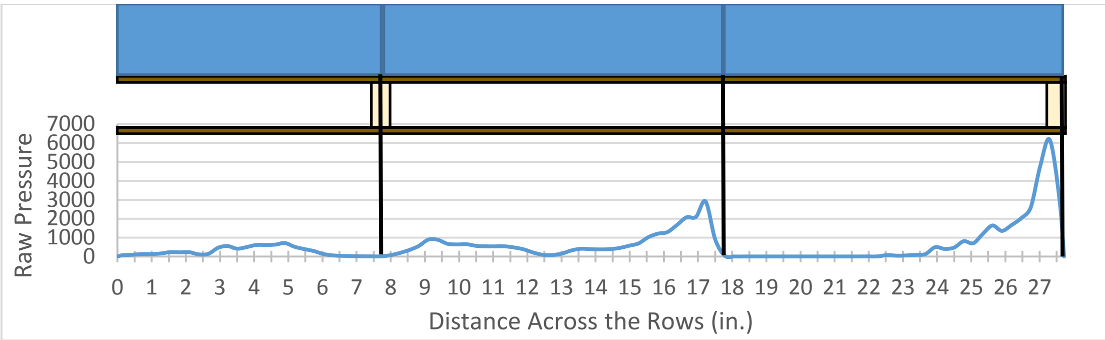

Figure 19 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using small boxes with 25.4 mm headspace.

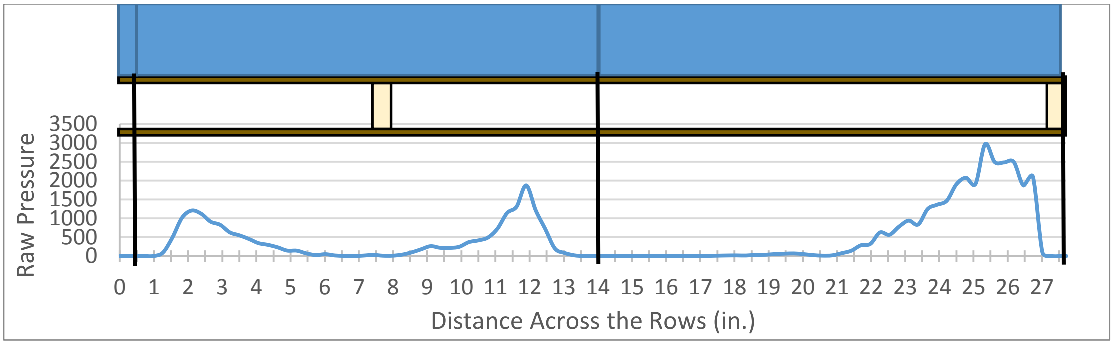

Figure 20 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using medium boxes with no headspace.

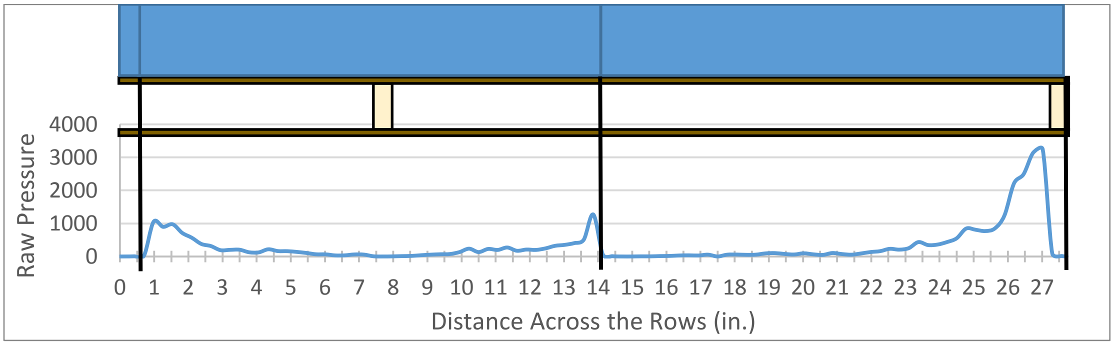

Figure 21 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using medium boxes with 25.4 mm headspace.

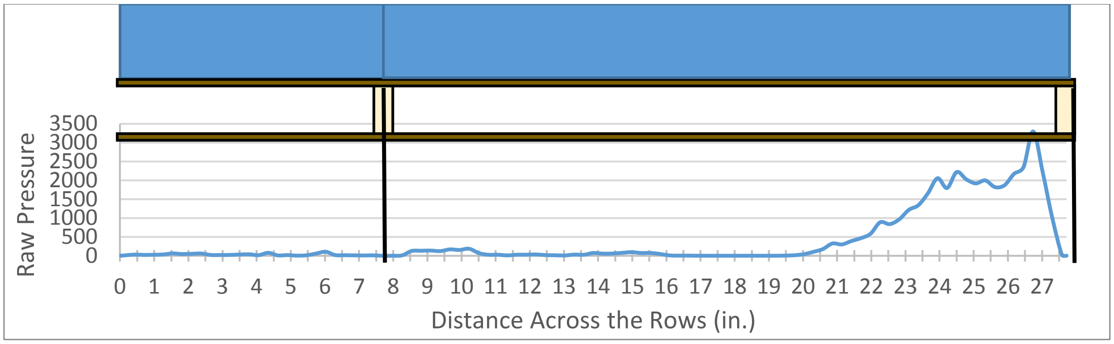

Figure 22 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using large boxes with no headspace.

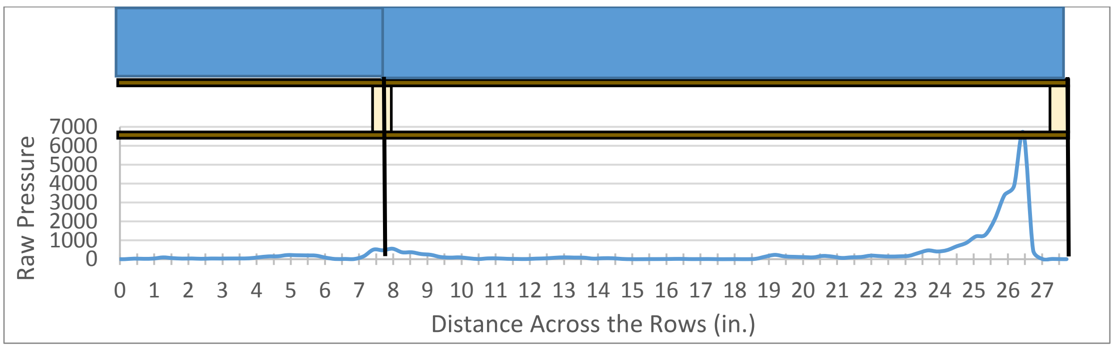

Figure 23 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the width condition using large boxes with 25.4 mm headspace.

In order to further understand how pressure distribution changes as the function of box size, the pressure distributed under the edges of the box were combined into a single concentrated force. The overall pressure distribution across the entire pallet is assumed to be symmetrical. The point loads presented for the small, medium, and large box conditions (in Figure 24 and Figure 25) demonstrates how the summation of sensels was done for the boxes. The percent of pressure that transfers down at each of the concentrated load points are calculated and presented (in Table 15 and Table 16) for all investigated treatments.

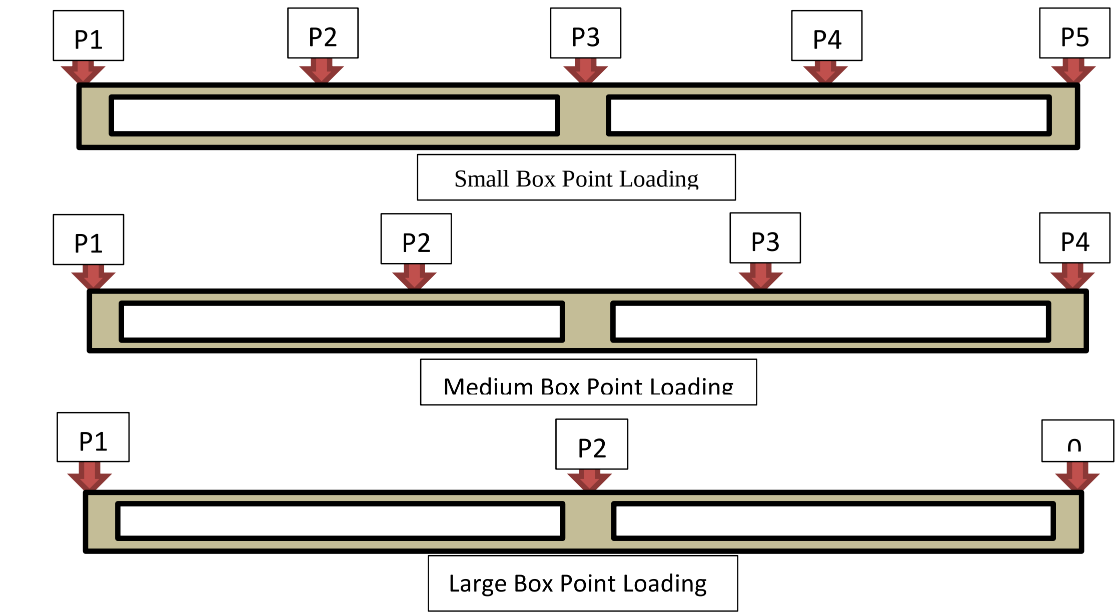

Figure 24 Estimated locations of the pressure distribution represented as concentrated loads on the top of the pallet.

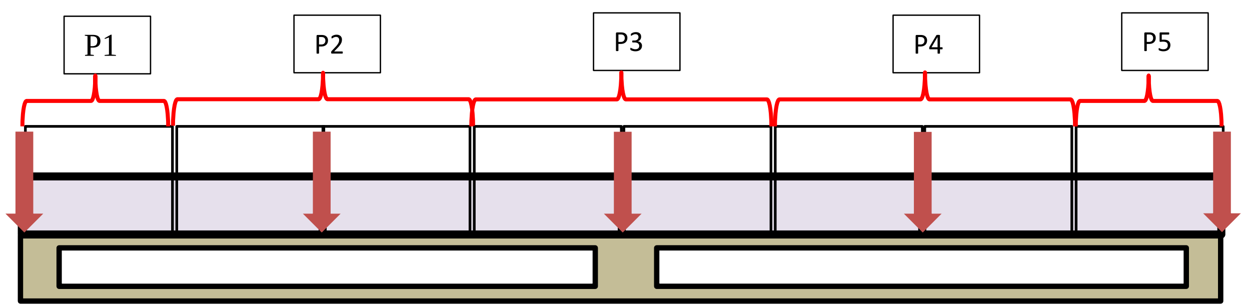

Figure 25 Example for the summation of the pressure across the entire pallet assuming a symmetrical load distribution for the warehouse racking support across the width for small boxes.

Table 15 The average percent of pressure estimated to be concentrated on the top of the pallet in the warehouse racking condition across the width if the pressure would be distributed as concentrated loads. All stiffness levels of pallets supporting boxes with no headspace.

		PRESSURE DISTRIBUTION AT THE CONCENTRATED PRESSURE POINTS				
PALLET STIFFNESS	Box Size	P1	P2	P3	P4	P5
LOW	Small	27.75% (2.84) A	16.80% (1.77) A	10.90% (2.12) A	16.80% (1.77) A	27.75% (2.84) A
	Medium	38.14% (1.03) A	11.86% (1.03) A		11.86% (1.03) A	38.14% (1.03) A
	Large	47.07% (0.58) A		5.86% (0.58) A		47.07% (0.58) A
MEDIUM	Small	28.11% (1.56) A	17.043% (1.64) A	9.70% (0.12) A	17.043% (1.64) A	28.11% (1.56) A
	Medium	34.91% (1.88) A	15.09% (1.88) A		15.09% (1.88) A	34.91% (1.88) A
	Large	44.83% (2.73) A		10.34% (2.73) A		44.83% (2.73) A
HIGH	Small	26.41% (2.76) A	14.77 (0.54) A	17.64% (2.98) A	14.77 (0.54) A	26.41% (2.76) A
	Medium	31.63% (4.74) A	18.37% (4.74) A		18.37% (4.74) A	31.63% (4.74) A
	Large	43.75% (1.03) A		12.50% (1.03) A		43.75% (1.03) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pressure distribution of one box size across different stiffness pallets at an alpha of 0.05.

Table 16 The average percent of pressure estimated to be concentrated on the top of the pallet in the warehouse racking condition across the width if the pressure would be distributed as concentrated loads. All stiffness levels of pallets supporting boxes with 25.4 mm of headspace.

		PRESSURE DISTRIBUTION AT THE CONCENTRATED PRESSURE POINTS				
PALLET STIFFNESS	Box Size	P1	P2	P3	P4	P5
LOW	Small	28.43% (1.94) A	17.21% (2.96) A	8.72% (2.85) A	17.21% (2.96) A	28.43% (1.94) A
	Medium	37.06% (0.90) A	12.94% (0.85) A		12.94% (0.85) A	37.06% (0.90) A
	Large	43.38% (0.23) A		13.24% (0.23) A		43.38% (0.23) A
MEDIUM	Small	26.46% (0.80) A	18.75% (0.89) A	9.58% (0.54) A	18.75% (0.89) A	26.46% (0.80) A
	Medium	32.84% (2.45) A	17.16% (2.45) B		17.16% (2.45) B	32.84% (2.45) A
	Large	37.51% (1.51) B		24.98% (1.51) B		37.51% (1.51) B
HIGH	Small	22.85% (0.38) B	19.86% (1.41) A	14.58% (1.77) A	19.86% (1.41) A	22.85% (0.38) B
	Medium	26.70% (3.15) B	23.36% (3.00) B		23.36% (3.00) B	26.70% (3.15) B
	Large	40.48% (0.83) C		19.04% (0.83) C		40.48% (0.83) C

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pressure distribution of one box size across different stiffness pallets at an alpha of 0.05.

During pallet testing, the percentage of pressure that is transferred to the top of the supports does not cause any bending of the pallet. Thus, reduced deflection of a pallet as a function of increasing box size can be explained by the increasing amount of pressure that is being redistributed to the supports. As the size of the boxes was increased from small (30.48cm x 25.40cm x 30.48cm) to large (50.80cm x 40.64cm x 30.48cm), the percent of pressure redistributed to the supports increased. High stiffness pallets ‘compressive stresses increased over the supports from 52.8% to 87.5% as the box size increased from small to large; using boxes with no headspace. The same significant pressure redistribution occurred when using boxes with 25.4mm of headspace: the pressure on the high stiffness pallets’ supports increased from 45.7% to 81%

6.2 Racked Support Across the Length Deflections

Deflection measurements for the warehouse racking support across the length condition were analyzed in the same fashion; separating the center and the end deflections of the pallets. The center deflections of the pallets are shown in Table 17, Table 18, Figure 26, and Figure 27. Table 20 and Table 21 show the end deflections for each of the pallet designs tested along with the three box sizes and the two headspace conditions. In Table 19 and Table 22, a 2-sample T-test was used to compare pallet deflections between those loaded with boxes both with and without headspace.

Table 17 Summary table of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the length with boxes that had no headspace and the decrease in deflection compared to the small box size.

AVERAGE PALLET DEFLECTION (MM)

BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	6.87(0.31) A		5.36(0.18) A		4.62(0.70) A	
MEDIUM	7.40(1.47) A	-7.71%	4.65(0.43) AB	13.25%	3.92(0.04) A	15.15%
LARGE	5.71(0.42) A	16.89%	4.39(0.35) B	18.10%	3.04(1.34) A	34.19%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 18 Summary table of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the length with boxes that 25.4 mm of headspace and the decrease in deflection compared to the small box size.

AVERAGE PALLET DEFLECTION (MM)

BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	7.15(0.04) A		5.57(0.16) A		4.82(0.74) A	
MEDIUM	5.71(0.13) B	20.14%	5.00(0.14) AB	10.23%	4.20(0.10) A	12.86%
LARGE	6.17(0.09) C	13.71%	4.70(0.53) B	15.62%	3.92(0.21) A	18.67%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 19 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the difference between center data deflections from no headspace and 25.4 mm headspace boxes during warehouse racking support across the length.

BOX SIZE	**LOW STIFFNESS PALLET**		**MEDIUM STIFFNESS PALLET**		**HIGH STIFFNESS PALLET**	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL	-1.61	0.25	1.47	0.24	0.34	0.75
MEDIUM	-2.00	0.184	1.34	0.31	4.53	0.05*
LARGE	1.83	0.21	0.86	0.46	1.11	0.38

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

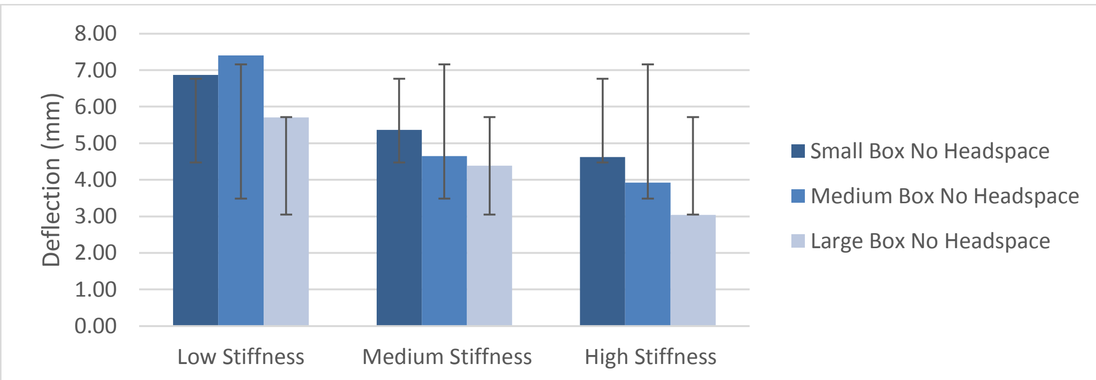

Figure 26 Graph of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the length for boxes with no headspace. The bars represent standard deviation.

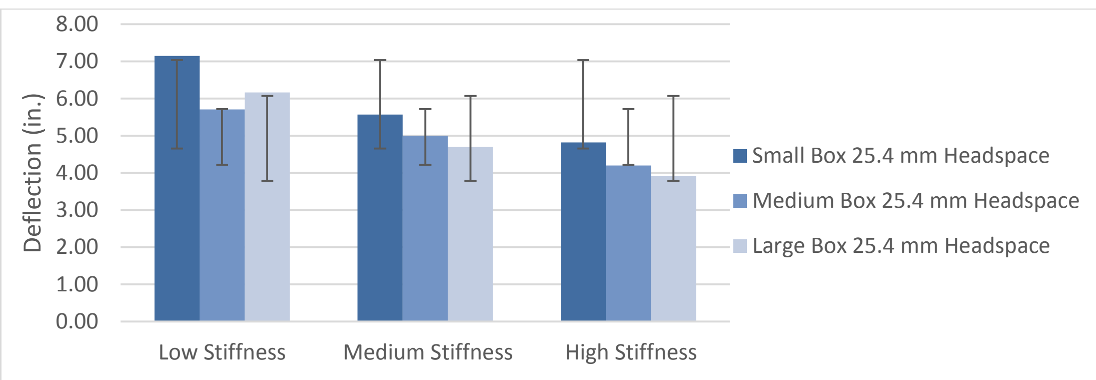

Figure 27 Graph of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the length for boxes with 25.4 mm. headspace. The bars represent standard deviation.

Table 20 Summary table of the average pallet deflection measured at the center of the pallet during the warehouse racking support across the length with boxes that have no headspace and the decrease in deflection compared to the small box size.

	AVERAGE PALLET DEFLECTION (MM)					
BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	4.43(0.53) A		3.93(0.28) A		3.22(0.64) A	
MEDIUM	4.14(0.53) A	6.55%	3.64(0.12) AB	7.38%	2.81(0.22) A	12.73%
LARGE	4.62(0.98) A	-4.29%	3.25(0.43) B	17.30%	2.73(0.90) A	15.22%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 21 Summary table of the average pallet deflection measured at the ends of the pallet during the warehouse racking support across the length with boxes that have 25.4 mm of headspace and the decrease in deflection compared to the small box size.

	AVERAGE PALLET DEFLECTION (MM)					
BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
SMALL	5.00(0.96) A		4.83(1.18) A		3.39(0.40) A	
MEDIUM	4.42(0.70) A	11.60%	3.52(0.34) B	27.12%	2.94(0.23) A	13.27%
LARGE	4.92(1.75) A	1.60%	3.60(0.57) B	25.47%	3.02(0.53) A	10.91%

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05

Table 22 Summary table showing the T-Values and P-Values from a 2-smaple T-test comparing the difference between ends data deflections from no headspace and 25.4 mm headspace boxes during warehouse racking support across the length.

BOX SIZE	**LOW STIFFNESS PALET**		**MEDIUM STIFFNESS PALLET**		**HIGH STIFFNESS PALLET**	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL BOX	-0.34	0.74	2.04	0.10	-0.35	0.73
MEDIUM BOX	1.32	0.22	-0.92	0.39	0.87	0.41
LARGE BOX	-0.56	0.59	1.26	0.24	0.64	0.54

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

Change in box size only had a statistically significant effect on deflection for the low (373,545n/m) and medium (664,080n/m) stiffness pallets. The ends of the pallets only show significant deflection differences between box sizes for the medium stiffness pallets. Overall, the center deflection values were still larger than the end deflection values. However, as with previous researchers, Collie (1982) and Fagan (1984), few statistical differences could be found. However, Park's (2017) observation that size affects deflection still holds true even in the warehouse racking support across the length condition. The largest statistically significant deflection change between small (30.48cm x 25.40cm x 30.48cm) and large (50.80cm x 40.64cm x 30.48cm) boxes was found on the medium stiffness pallets (18%) with boxes that had no headspace. The lack of statistically significant differences can be attributed to the considerably high pallet stiffness in this support condition causing small deflection values.

Similarly to the racking across the width support condition, there were no significant differences found between the pallet deflection measurements for boxes with no head space and those with 25.4mm head space for most pallet stiffness and box size combinations. Therefore, it appears that the headspace variable of a box has no practical effect on pallet deflection in the racking support condition.

6.2.1 Racked Support Across the Length Pressure Readings

The 7202N TekScan™ pressure mat recorded the distribution of pressures on the top surface of the pallet. The following figures demonstrate how all pressure mat data was analyzed to observe the compressive forces on the pallet. Figure 28 shows the pressure distribution on low stiffness pallets in a warehouse racking support across the length condition with the various box variables. To visualize the pressure distribution across the pallet in the racking supports, the data from the pressure sensels are presented in Figure 29 to Figure 34. In each of these figures, there is a graphical representation of where the pallet components and boxes are in relation to the peaks of summed sensels.

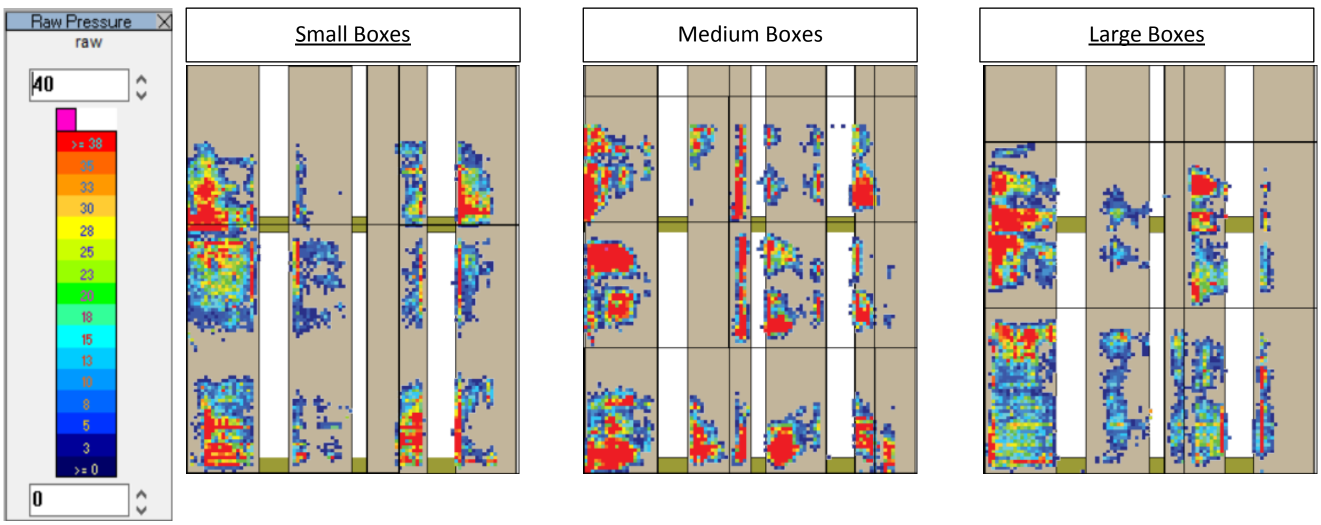

Figure 28 Pressure distribution example on the top surface of the pallet during a racked support across the length for 25.4 mm headspace scenarios using different box sizes on the lowest stiffness pallet. The legend to the left indicates value for the colors that are obtained from the TekScan™ pressure mat.

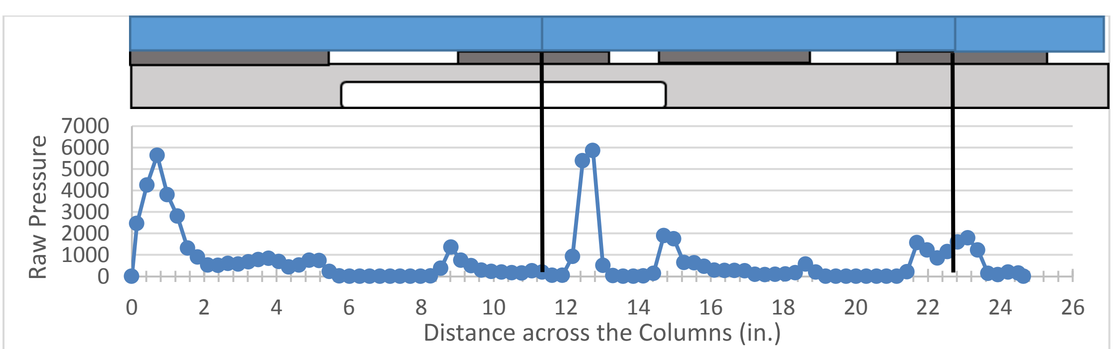

Figure 29 Pressure distributions on the top surface of the pallet summed up along the width of the pallet for warehouse rack support across the length condition using small boxes with no headspace.

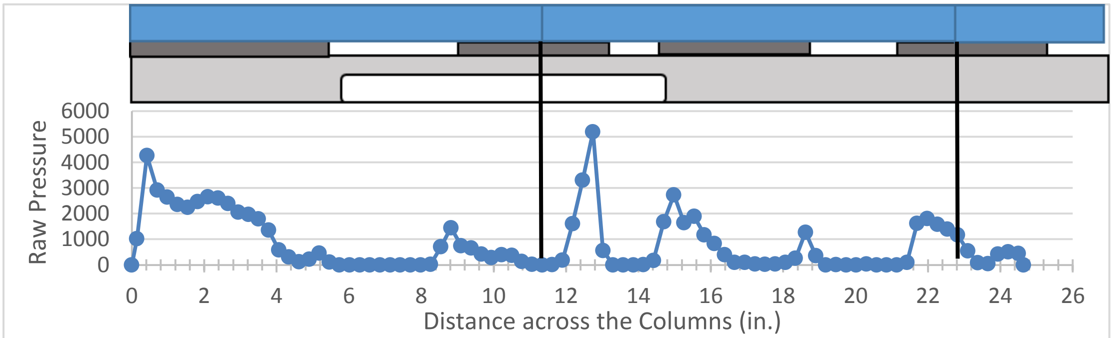

Figure 30 Pressure distributions on the top surface of the pallet summed up along the width length of the pallet for warehouse rack support across the length condition using small boxes with 25.4 mm headspace.

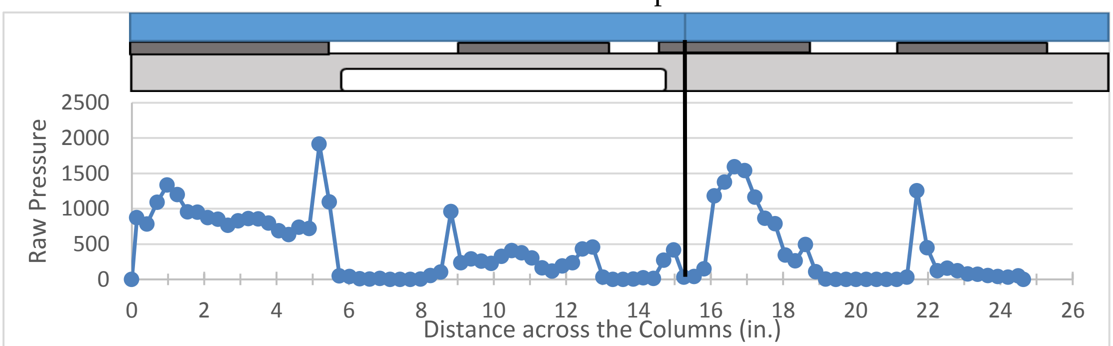

Figure 31 Pressure distributions on the top surface of the pallet summed up along the width of the pallet for warehouse rack support across the length condition using medium boxes with no headspace.

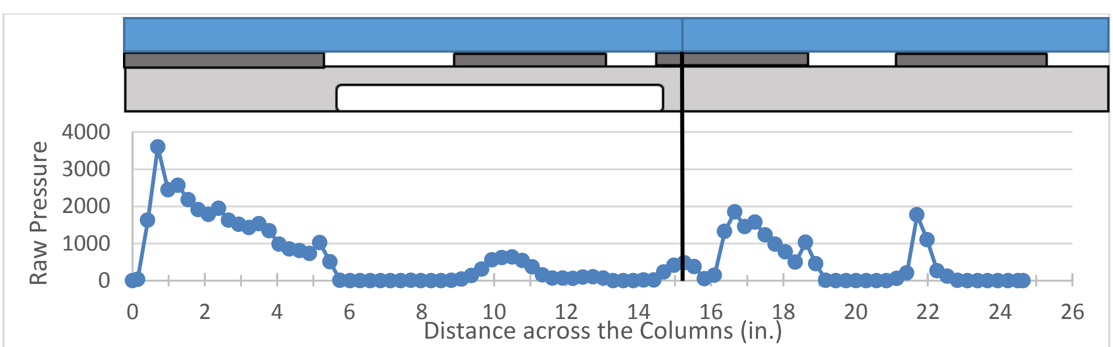

Figure 32 Pressure distributions on the top surface of the pallet summed up along the width of the pallet for warehouse rack support across the length condition using medium boxes with 25.4 mm headspace.

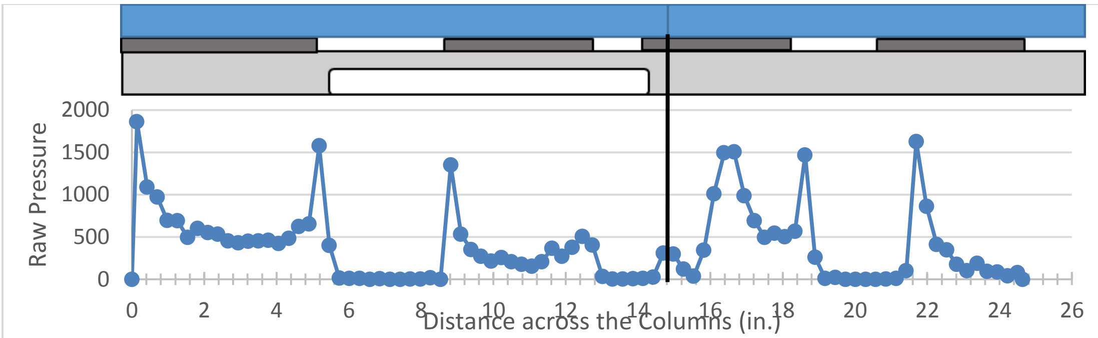

Figure 33 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the length condition using large boxes with no headspace.

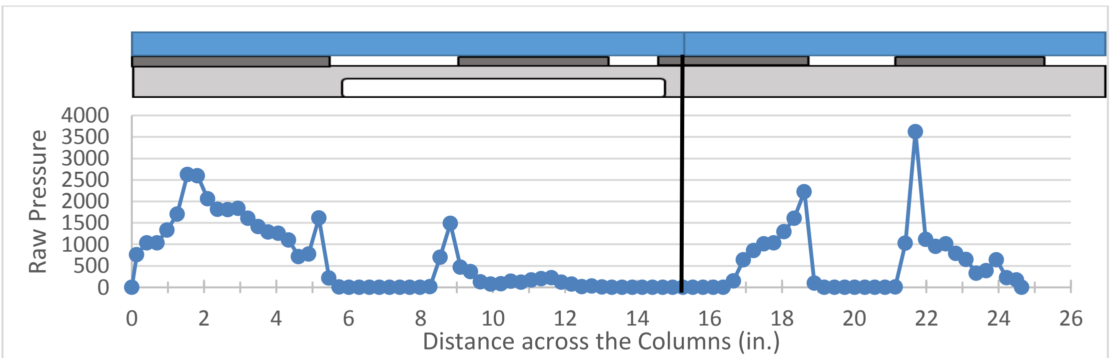

Figure 34 Pressure distributions on the top surface of the pallet summed up along the length of the pallet for warehouse rack support across the length condition using large boxes with 25.4 mm headspace.

In order to further understand the how pressure distribution changes as a function of box size, the pressures distributed on individual deck boards (Figure 35) were combined into a single concentrated force (Figure 36). For this conversion, the overall pressure distribution across the entire pallet is assumed to be symmetrical. The amount of pressure distributed across the different deck boards of the top deck is shown in Table 23 and Table 24.

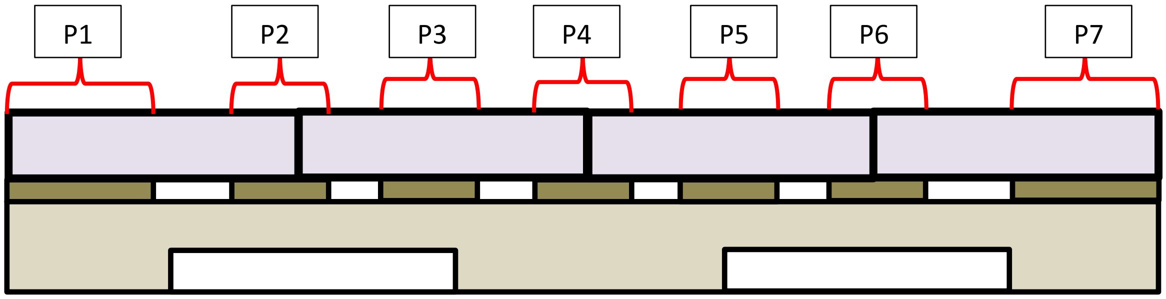

Figure 35 The summation of the pressure across the entire pallet assuming a symmetrical load distribution using data collected from the pressure mat. In this warehouse racking support across the length the boxes are exerting pressure to the deck boards.

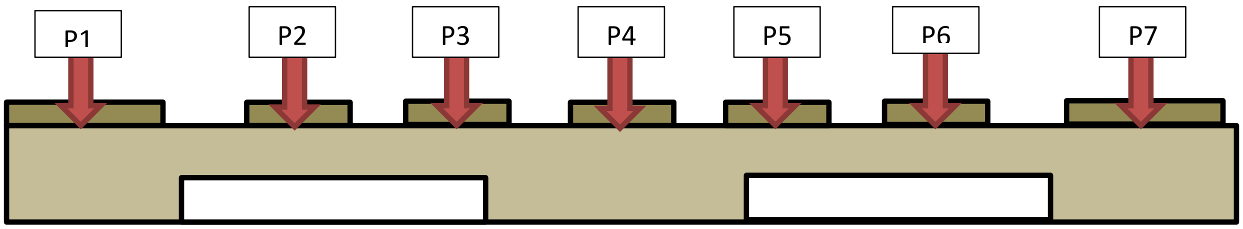

Figure 36 The averaged pressure distribution for each box size (small, medium, and large) grouped into point loads to localize where the percentage of pressure is being redistributed to the deck boards due to box size

Table 23 The average percent of pressure estimated to be concentrated on the top of the pallet in the warehouse racking condition across the length if the pressure would be distributed as concentrated loads. All stiffness levels of pallets supporting boxes with no headspace.

		PRESSURE DISTRIBUTION AT THE CONCENTRATED PRESSURE POINTS						
PALLET STIFFNESS	Box Size	P1	P2	P3	P4	P5	P6	P7
LOW	Small	27.39% (1.26) A	4.73% (0.58) A	10.50% (0.97) A	14.77% (0.77) A	10.50% (0.97) A	4.73% (0.58) A	27.39% (1.26) A
	Medium	29.39% (1.13) A	4.26% (0.75) A	12.75% (1.21) A	7.20% (0.83) A	12.75% (1.21) A	4.26% (0.75) A	29.39% (1.13) A
	Large	30.87% (2.03) A	5.69% (0.83) A	4.42% (1.52) A	18.02% (1.54) A	4.42% (1.52) A	5.69% (0.83)A	30.87% (2.03) A
MEDIUM	Small	24.53% (0.61)AB	5.73% (0.81) B	11.71% (1.13) A	16.06% (0.51) A	11.71% (1.13) A	5.73% (0.81) B	24.53% (0.61)AB
	Medium	25.59% (0.88) B	6.75% (1.57) A	14.34% (2.08) A	6.64% (0.37) A	14.34% (2.08) A	6.75% (1.57) A	25.59% (0.88) B
	Large	28.97% (2.29) A	5.92% (2.63)A	5.92% (1.38)A	18.38% (0.37)A	5.92% (1.38)A	5.92% (2.63)A	28.97% (2.29) A
HIGH	Small	23.37% (1.99)B	7.80% (0.35) B	10.72% (2.01) A	16.22% (1.13) A	10.72% (2.01) A	7.80% (0.35) B	23.37% (1.99)B
	Medium	25.87% (0.21) B	6.12% (1.07) A	15.41% (1.16) A	5.20% (0.82) A	15.41% (1.16) A	6.12% (1.07) A	25.87% (0.21) B
	Large	30.62% (2.24) A	7.81% (0.63) A	3.33% (0.83) A	16.48% (3.51) A	3.33% (0.83) A	7.81% (0.63) A	30.62% (2.24) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pressure distribution of one box size across different stiffness pallets at an alpha of 0.05.

Table 24 The average percent of pressure estimated to be concentrated on the top of the pallet in the warehouse racking condition across the length if the pressure would be distributed as concentrated loads. All stiffness levels of pallets supporting boxes with 25.4 mm headspace.

		PRESSURE DISTRIBUTION AT THE CONCENTRATED PRESSURE POINTS						
PALLET STIFFNESS	Box Size	P1	P2	P3	P4	P5	P6	P7
LOW	Small	25.70% (2.00) A	8.57% (3.68) A	5.63% (1.55) A	20.20% (0.80) A	5.63% (1.55) A	8.57% (3.68) A	25.70% (2.00) A
	Medium	18.84% (10.38) A	9.31% (5.06) A	16.17% (3.90) A	11.38% (2.04) A	16.17% (3.90) A	9.31% (5.06) A	18.84% (10.38) A
	Large	18.92% (2.63) A	7.41% (1.31) A	17.88% (4.14) A	11.56% (1.10) A	17.88% (4.14) A	7.41% (1.31) A	18.92% (2.63) A
MEDIUM	Small	23.55% (0.55) AB	9.05% (0.45) A	6.41% (0.07) A	21.98% (0.21) A	6.41% (0.07) A	9.05% (0.45) A	23.55% (0.55) AB
	Medium	21.72% (1.17) A	5.71% (1.05) A	19.53% (0.39) A	6.10% (0.41) AB	19.53% (0.39) A	5.71% (1.05) A	21.72% (1.17) A
	Large	18.3% (5.49) A	6.98% (1.69) A	15.01% (5.66) A	12.76% (1.65) A	15.01% (5.66) A	6.98% (1.69) A	18.3% (5.49) A
HIGH	Small	21.09% (0.97) B	10.37% (1.90) A	8.06% (3.69) A	20.98% (1.88) A	8.06% (3.69) A	10.37% (1.90) A	21.09% (0.97) B
	Medium	19.3% (2.88) A	8.00% (0.69) A	20.42% (2.16) A	4.54% (0.45) B	20.42% (2.16) A	8.00% (0.69) A	19.3% (2.88) A
	Large	15.38% (5.28) A	8.53% (0.49) A	21.23% (3.90) A	9.72% (0.99) A	21.23% (3.90) A	8.53% (0.49) A	15.38% (5.28) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pressure distribution of one box size across different stiffness pallets at an alpha of 0.05.

As the size of the boxes increased from small (30.48cm x 25.40cm x 30.48cm) to large (50.80cm x 40.64cm x 30.48cm), the percent of pressure that was redistributed to the supports only decreased slightly. On the medium stiffness pallet, compressive stresses on the support decreased from 58.78% to 51.74% as the box size increased from small to large with no headspace. The discrepancy between the observed pressure redistribution and the pallet deflection could be the result of the small pallet deflection values. However, the lack of correlation needs to be further investigated.

6.3 Fork Tine Support Across the Width Deflections

The deflections were averaged and analyzed together for each variables of such as box size, box headspace conditions, and pallet stiffness treatments. The results are presented in Table 25, Figure 37 *and* Figure 38. The measurements between headspace boxes and no headspace boxes were analyzed together with a 2-sample T-test to compare the pallet deflections in Table 26.

The boxes with no headspace and 25.4 mm of headspace showed no statistical difference except for the medium boxes on the high stiffness pallet. The lack of significant difference between the headspace and not headspace conditions could be due to the low deflection values that occur during fork tine support. Other studies, have also demonstrated the small amount of deflection and the lack of statistical significance that happens during the fork tine support across the width condition (White, 2008; Molina, 2017).

Table 25 Summary table of the average pallet deflections during the fork tine support across the width using boxes with and without headspace.

	AVERAGE PALLET DEFLECTION (MM)					
BOX SIZE	Low Stiffness		Medium Stiffness		High Stiffness	
	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace
SMALL	1.14(0.82) A	1.48 (1.60) A	0.78(1.04) A	1.01(0.63) A	0.64(1.56) A	0.43(0.77) A
MEDIUM	1.02(1.52) A	0.36(0.79) A	0.90(0.99) A	0.20(1.45) A	0.58(0.67) A	0.43(1.41) A
LARGE	0.95(0.67) A	-0.13(2.98) A	0.57(0.59) A	-0.06(1.18) A	0.88(0.89) A	0.88(0.89) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results using Tukey HSD comparing the pallet deflection measured using the different box sizes on the same stiffness pallet at an alpha of 0.05.

Table 26 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the difference between averaged pallet deflections from no headspace and 25.4 mm headspace boxes during the fork tine support across the width.

BOX SIZE	LOW STIFFNESS		MEDIUM STIFFNESS		HIGH STIFFNESS	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL	-0.64	0.53	0.67	0.51	-0.41	0.69
MEDIUM	1.34	0.20	-1.38	1.83	-2.24	0.04*
LARGE	-1.23	0.24	-1.64	0.12	0.00	1.00

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

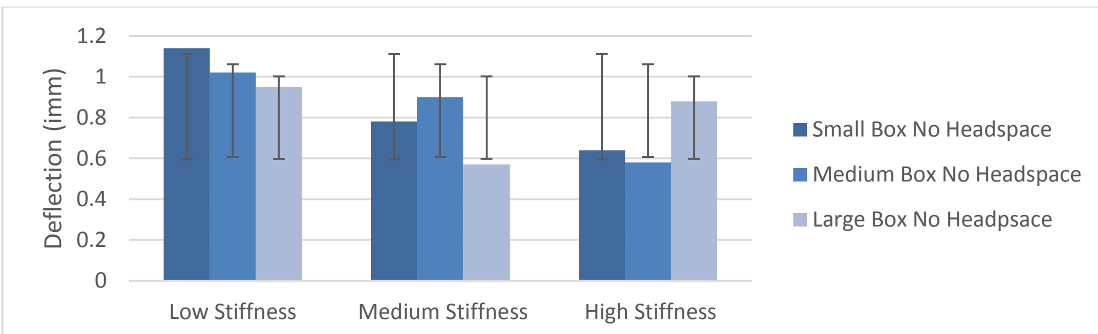

Figure 37 Graph of the average pallet deflections for fork tine support across the width condition using boxes with no headspace and three pallet designs. The bars represent standard deviation.

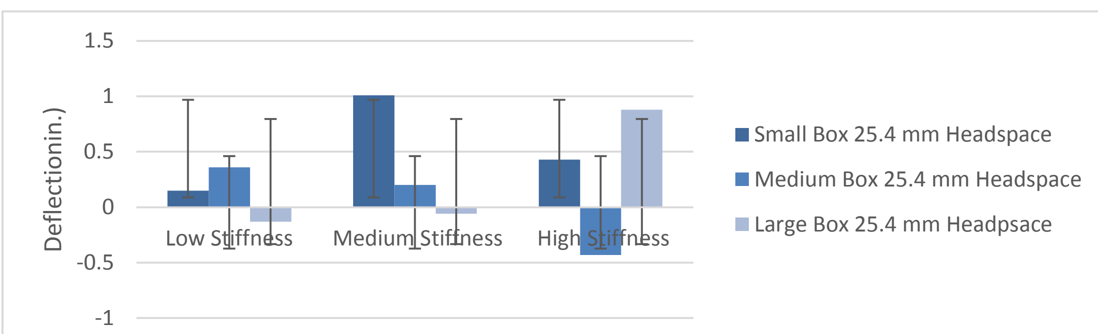

Figure 38 Graph of the average pallet deflections for fork tine support across the width condition using boxes with 25.4 mm headspace and three pallet designs. The bars represent standard deviation.

6.4 Fork Tine Support Across the Length Deflections

The deflections were averaged and analyzed together for each of the variables such as box size, box headspace condition, and pallet stiffness. The results are presented in Table 27, Figure 39, and Figure 40. A statistical analysis for the deflection measurements for boxes both with and without headspace is shown in Table 28.

There were no statistically significant trends to be found between the deflection of the pallet and increasing box sizes using the fork tine support across the length condition. The two headspace conditions also showed no statistically significant differences. However, due to the small deflection values and high standard deviations, more detailed investigation is recommended using an increased sample size.

The low levels of deflection and lack of significant differences between the headspace conditions can be attributed to the high stiffness of pallet components in the investigated pallet direction. Previous studies (Collie, 1982; Fagan, 1984; White 2008) investigating racking support conditions across the length found that there is little difference in deflection even with increasing loads mostly due to the much greater pallet stiffness in racked across the length.

There was also no statistical difference to be found in deflection as a function of the different box sizes. Again, this could be due to the small deflection values and high standard deviations. Similar to the warehouse racking support condition when the pallet was racked across its length, the stringers are the main components under stress during this support condition, and they bend little when compared to the racking across the width condition.

Table 27 Summary table of the average pallet deflections during the fork tine support across the length using boxes with and without headspace.

AVERAGE PALLET DEFLECTION (MM)

BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace
SMALL	1.13(1.24) A	0.36(0.68) A	0.36(1.50) A	0.28(1.02) A	0.63(1.63) A	0.31(1.17) A
MEDIUM	0.10(1.77) A	0.70(0.48) A	1.00(1.68) A	0.89(2.53) A	0.97(1.60) A	0.07(1.68) A
LARGE	1.12(1.05) A	0.48(0.46) A	-0.50(0.60) A	2.73(2.08) A	0.71(1.69) A	0.71(1.69) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results measured by Tukey HSD at 0.05 alpha.

Table 28 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the difference between averaged pallet deflections from no headspace and 25.4 mm headspace boxes during the fork tine support across the length.

BOX SIZE	LOW STIFFNESS PALLET		MEDIUM STIFFNESS PALLET		HIGH STIFFNESS PALET	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL BOX	1.88	0.08	-0.16	0.88	0.54	0.60
MEDIUM	1.13	0.28	-0.13	0.90	1.34	0.19
LARGE BOX	-1.94	0.07	1.78	0.10	0	1.00

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq0$.
The deflection values were compared using 2 sample T-test comparison
* = Variable that rejects the null hypothesis.

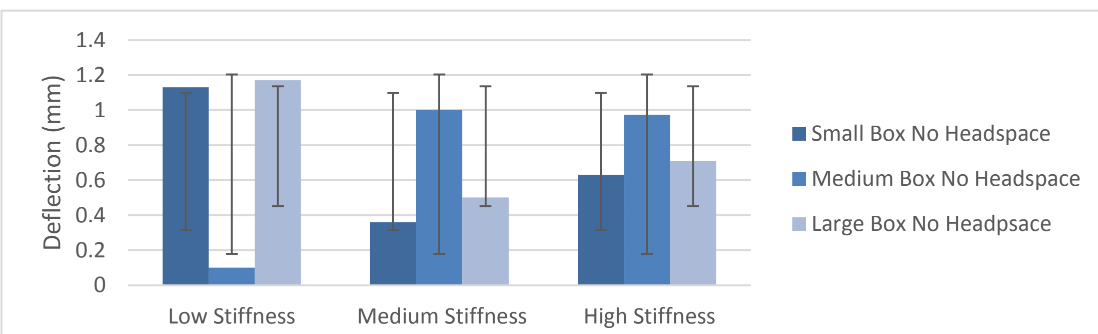

Figure 39 Graph of the average pallet deflections for fork tine support across the length condition using boxes with no headspace and three pallet designs. The bars are for standard deviation.

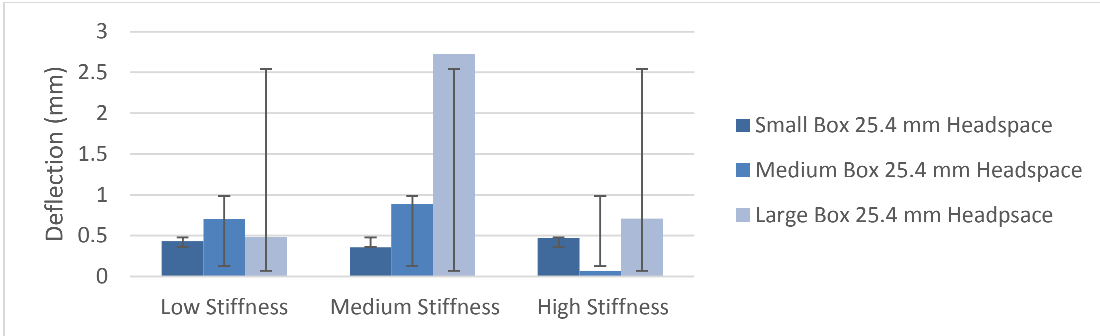

Figure 40 Graph of the average pallet deflections for fork tine support across the length condition using boxes with 25.4 mm headspace and three pallet designs. The bars are for standard deviation.

6.5 Floor Support Single Stack Top Deckboard Deflections

For the floor support condition using a single stacked unit load, top deck board deflection measurements were only taken for the deck boards that were covered by the mat. The deflections from each top deck board were averaged together for each of the test replicates. The results are presented in Table 29, Figure 42, and Figure 43. A statistical analysis of the deflection measurements between the boxes with and without headspace is shown in Table 30.

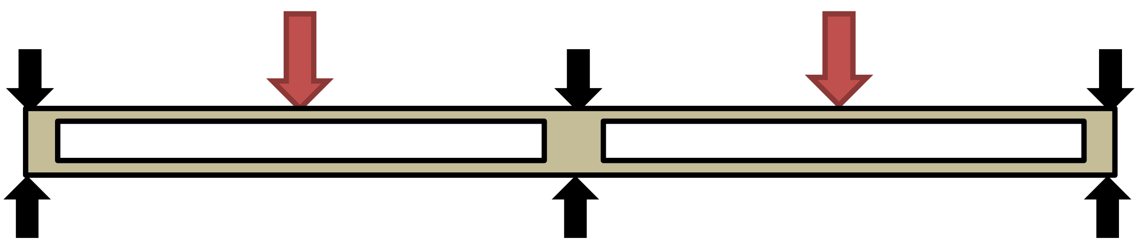

Figure 41 Simplified force diagram for the loading of the pallet and its components in a floor support single stack.

Table 29 Summary table of the average pallet deflection measured at the center of the deck board during the single stack floor stacking support using boxes with and without headspace.

BOX SIZE	AVERAGE PALLET DEFLECTION (MM)					
	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace
SMALL	1.09(0.38) A	0.67(0.52) A	0.58(0.30) A	0.57(0.22) A	0.33(0.12) A	0.45(0.25) A
MEDIUM	1.25(0.34) A	0.98(0.27) A	0.84(0.22) A	0.50(0.27) A	0.47(0.27) A	0.42(0.32) A
LARGE	1.00(0.33) A	0.77(0.33) A	0.67(0.32) A	0.73(0.33) A	0.48(0.18) A	0.33(0.23) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results measured by Tukey HSD at 0.05 alpha.

Table 30 Summary table showing the T-Values and P-Values from a 2-sampleT-test comparing the difference between averaged pallet top deckboard deflections from no headspace and 25.4 mm headspace boxes during single stack floor stacking support.

BOX SIZE	LOW STIFFNESS PALET		MEDIUM STIFFNESS PALET		HIGH STIFFNESS PALET	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL	-2.30	0.03*	-0.08	0.93	1.54	0.14
MEDIUM	-2.18	0.04*	-3.42	0.00*	0.43	0.67
LARGE	-1.66	0.11	0.43	0.67	-1.84	0.08

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

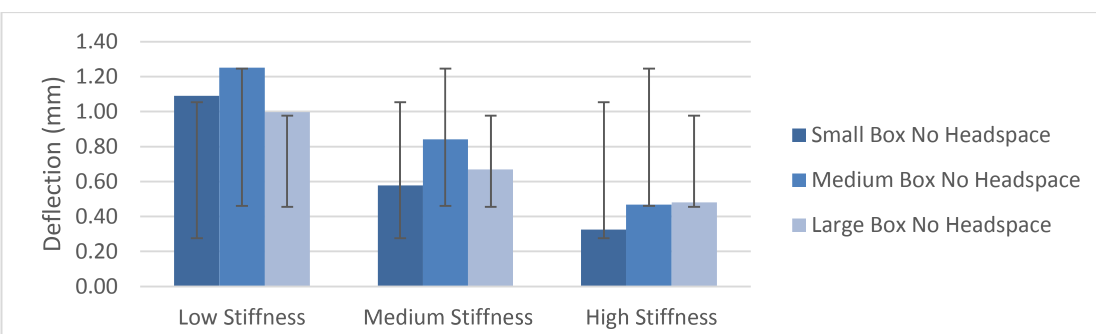

Figure 42 Graph of the average pallet deflections for the single stacked floor stacking support using boxes with no headspace and three pallet designs. The bars are for standard deviation.

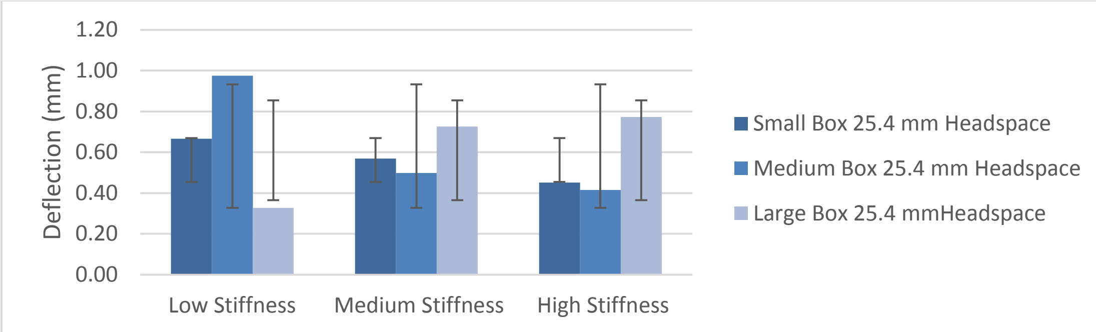

Figure 43 Graphs of the average pallet deflections for the single stacked floor stacking support using boxes with headspace and three pallet designs. The bars are for standard error.

The pallet deflection measurements for the different box sizes were not statistically different from each other (Table 30). If we analyze the support in detail, the lower deflection results may be explained by the loading of the pallet components. During the floor support condition, the stringers are all fully supported, and the deck boards in-between the stringers are the only components able to bend (Figure 41). To draw a comparison, the deck boards across the inner and outer stringers are like a warehouse racking support across the width condition but with only half of the free span. Collie (1984) found that for floor support scenarios neither the pallet stiffness nor load type significantly affect load distribution. Therefore, due to the load bridging phenomena, the load applied to the top deckboards might not be great enough to cause any significant deflection and to result in a statistical difference.

The effect of headspace was only statistically different using small and medium boxes on the low stiffness pallet and medium boxes on the medium stiffness pallet. The presence of headspace increased the pallet top deck deflection by 39% when small boxes and 22% when medium boxes were tested on the low stiffness pallet. The difference in deflection between no headspace and 25.4 mm of headspace for medium boxes on the medium stiffness pallets was a 41% difference.

6.5.1 Floor Support Double Stack Top Deckboard Deflections

For the floor support condition using a double stacked unit load, the top deck board deflection measurements were only taken for the deck boards that were covered by the mat. The deflections from each board were averaged together to create an average deflection of the top deck boards of the first pallet. The results are presented in *Table 31*, Figure 44, and Figure 45. The statistical analyses of the deflection measurements for the boxes both with and without headspace are shown in Table 32.

Table 31 Summary table of the average top pallet deckboard deflection measured at the center of the deck board during the double stack floor stacking support using boxes with and without headspace.

BOX SIZE	AVERAGE PALLET DEFLECTION (MM)					
	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace
SMALL	1.88(0.41) A	1.49(0.45) A	0.96(0.25) A	1.10(0.42) A	0.61(0.17) A	0.86(0.45) A
MEDIUM	2.13(0.43) A	1.85(0.38) AB	1.22(0.33) A	1.03(0.39) A	0.84(0.29) A	0.65(0.43) A
LARGE	1.80(0.72) A	1.23(0.77) B	1.13(0.43) A	1.42(0.97) A	0.63(0.28) A	0.63(0.28) A

Note: The numbers in parentheses are the standard deviation. The numbers with different capital letters indicate statistically significant results measured by Tukey HSD at 0.05 alpha.

Table 32 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the difference between averaged pallet top deckboard deflections from no headspace and 25.4 mm headspace boxes during double stack floor stacking support.

BOX SIZE	LOW STIFFNESS PALLET		MEDIUM STIFFNESS PALLET		HIGH STIFFNESS PALLET	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL BOX	2.22	0.04*	0.99	0.34	-1.81	0.09
MEDIUM	-1.67	0.11	-1.28	0.21	-1.29	0.21
LARGE BOX	-1.88	0.07	0.95	0.36	0.00	1.00

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq 0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

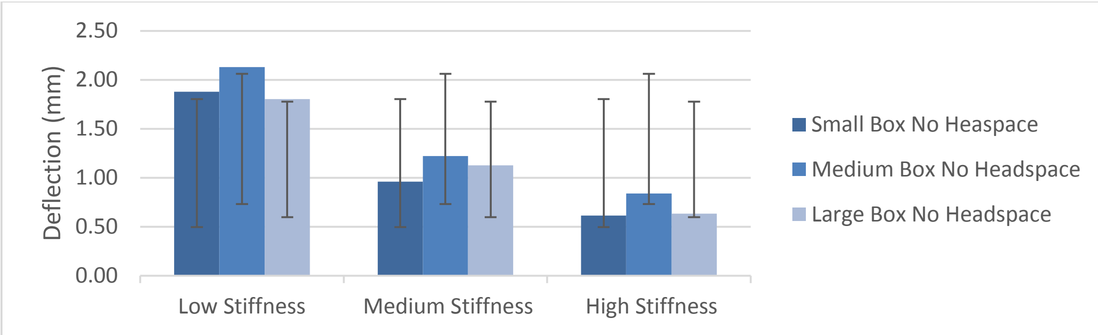

Figure 44 Graph of the average top pallet deckboard deflections for the double stacked floor stacking support using boxes with no headspace and three pallet designs. The bars are for standard deviation.

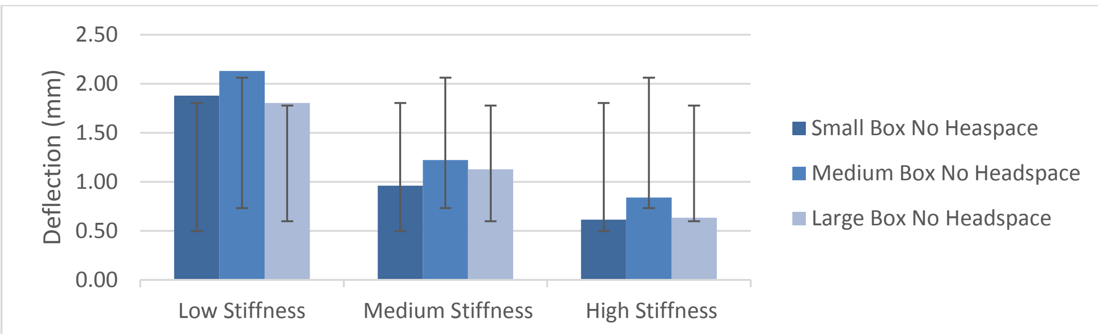

Figure 45 Graph of the average top pallet deckboard deflections for the double stacked floor stacking support using boxes with 25.4mm of headspace and three pallet design. The bars are for standard deviation.

The pallet deflection measurements for the different box sizes were not statistically different from each other except for the low stiffness pallet loaded with boxes with 25.4mm headspace. The pallet deflection decreased 17% when the box size was increased from small to large. The effect of headspace was only significant for small boxes on low stiffness pallets (Table 32*)*. Similarly to the single stacked floor support condition, the weight on the pallet might be too low to distribute the weight enough to deflect the deck boards significantly.

6.6 Floor Support Double Stack Bottom Deckboard Deflections

For the floor support condition using a double stacked unit load, the bottom deck board deflection measurements were only taken for the deck boards that were covered by the mat. The deflections from each board were averaged together to create an average deflection of the bottom deck boards of the first pallet. The results are presented in *Table* 33, Figure 46, and Figure 47. A statistical analysis of the deflection measurements for the boxes with and without headspace is shown in Table 34.

Table 33 Summary table of the average bottom pallet deckboard deflection measured at the center of the deck board during the double stack floor stacking support using boxes with and without headspace.

AVERAGE PALLET DEFLECTION (MM)

BOX SIZE	Low Stiffness Pallet		Medium Stiffness Pallet		High Stiffness Pallet	
	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace	No Headspace	25.4 Headspace
SMALL	1.47(0.69) A	1.26(0.34) A	1.28(0.55) A	1.17(0.33) A	0.62(0.27) A	0.80(0.27) A
MEDIUM	1.46(0.45) A	1.53(0.62) A	1.28(0.35) A	0.99(0.29) A	0.79(0.44) A	0.88(0.23) A
LARGE	1.79(1.26) A	0.83(0.86) A	0.63(0.26) B	0.93(0.81) A	0.56(0.27) A	0.46(0.30) B

Note: The numbers with different capital letters indicate statistically significant results measured by Tukey HSD at 0.05 alpha.

Table 34 Summary table showing the T-Values and P-Values from a 2-sample T-test comparing the difference between averaged pallet bottom deckboard deflections from no headspace and 25.4 mm headspace boxes during double stack floor stacking support.

BOX SIZE	LOW STIFFNESS PALLET		MEDIUM STIFFNESS PALLET		HIGH STIFFNESS PALLET	
	T-Value	P-Value	T-Value	P-Value	T-Value	P-Value
SMALL BOX	0.81	0.44	-0.53	0.60	1.43	0.17
MEDIUM	-0.24	0.81	2.85	0.02*	-0.56	0.59
LARGE BOX	-1.88	0.08	1.06	0.32	-0.78	0.45

Note: Null Hypothesis: $H_0=\mu_1-\mu_2=0$ Alternate Hypothesis: $H_0=\mu_1-\mu_2\neq0$.
The deflection values were compared using 2 sample T-test comparison.
* = Variable that rejects the null hypothesis.

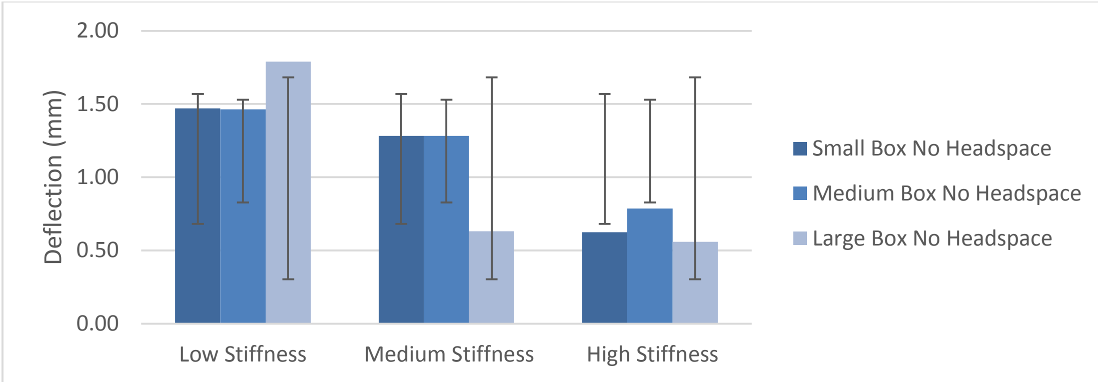

Figure 46 Graphs of average bottom pallet deckboard deflections for the double stacked floor stacking support using boxes with no headspace and three pallet designs. The bars are for standard deviation.

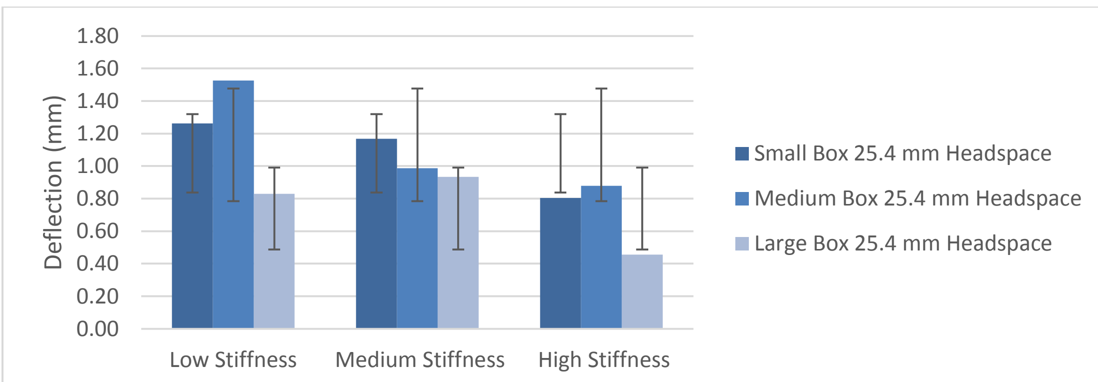

Figure 47 Graphs of average bottom pallet deckboard deflections for the double stacked floor stacking support using boxes with no headspace and three pallet designs. The bars are for standard deviation.

The effect of box size was not significant for most pallet stiffness and box size combinations, except the large boxes on medium stiffness pallets (51% difference) and high stiffness pallets (42% difference). The only difference (of 23%) to be found between the two headspace conditions was with the medium boxes on the medium stiffness pallets (Table 34).

7 Conclusion

The box size had a significant effect on the pallet deflection for all of the evaluated pallet stiffnesses using a warehouse racking support across the width (RAW). This support condition showed the greatest reduction in pallet deflection out of the six support conditions performed. The deflection of the pallet decreased for all pallet stiffness levels as the box size increased. Using boxes with a 25.4 mm headspace on the high stiffness pallet, a 53% reduction in pallet deflection was observed as the box size increased from small to large with headspace.

When the distribution of the compression pressure was investigated it was found that with an increase in box size more pressure is distributed from the center of the pallet towards the support. The pressure on the top of the supports increased from 45.7% to 81% using high stiffness pallets supporting boxes with 25.4 mm headspace when the size of the box increased from small to large. More pressure is concentrated on the top of the supports less pressure cause stresses in the pallet thus the load capacity of certain type of pallets can possibly be increased.

For the warehouse racking support across the length (RAL), the box size only had a significant effect on the pallet deflection using the low and medium stiffness pallets. The largest reduction in deflection was 18.1% for boxes without any headspace on the medium stiffness pallet as the box size increased from small to large. The smaller effect of the box size on the pallet deflection in the racked across the length support condition could be artefact of the much higher pallet stiffness in this direction. Less the pallet bends under load, less prominent effect the size of corrugated boxes has on the pressure redistribution. When the pressure redistribution was investigated it was found that the pressure redistribution only changed 7% compared to the 35.3% change for the racked across the width support condition.

The box size had no significant effect using the investigated pallet stiffness's for the fork tine support across the width, fork tine support across the length, and the single stack top deck floor support. This lack of significance was attributed to the very small deflections associated with the supports at the measured locations that were observed.

Under the double stack top deck floor support condition, only the large box with a 25.4 mm headspace on the low stiffness pallet showed a significant effect of box size on pallet deflection. There was 17% reduction in deflection when the box size was increased from small to large. The double stack bottom deckboards also showed a significant effect in the deflection based on box size. The deflection of the bottom deckboard of the medium stiffness pallet supporting boxes with no headspace and the deflection of the high stiffness pallet supporting boxes with headspace decreased 51% and 42% respectively when the box size was increased from small and large.

Although, the effect of headspace was found to be significant for some pallet stiffness and box size combinations, no consistent trend in the results pallet deflections was found. It is hypothesizes, that the lack of consistency could have been the artefact of the low sample size. Thus using a larger sample size is recommended to determine the exact effect of the headspace on pallet deflection.

The compressive pressures across the top of the pallet surfaces redistributed towards the supports when box size increased. The greatest difference in pressure redistribution was observed in the warehouse racking across the width support condition. The pressure on the top of the supports increased from 45.7% to 81% using high stiffness pallets supporting boxes with 25.4 mm headspace when the size of the box increased from small to large. The warehouse racking across the length support condition showed the redistribution phenomenon as well, but the pressure is distributed in a more even manner across the top deckboards with a slight concentration on the lead deckboards. As more of the compressive forces redistribute across the top of the pallet to the supports, the deflection along the free span decreases. This can increase the load capacity of certain pallet designs. Therefore, to increase the sustainability of pallets and to conserve resources, it’s recommended that the pallet is always designed with the product’s packaging design in mind.

8 Recommendations for Further Research

Based on the results and data from this research, it would benefit unit load design to further explore the load bridging effect in order to improve the understanding of this phenomenon. The following recommendations for future research can be made from this experiment:

1. Continue pursuing the same tests to analyze the effect of the box size on load bridging, but perform the experimental design with a larger sample size in order to clarify some of the data that showed no significance and to simply have a larger amount of data to validate and expand on this experiment.
2. Perform the same tests with varying weight loads that would provide a load stiffness ratio of at least 8, in order to ensure a significant amount of load bridging is occurring for each different support.
3. Develop a model using the pressure percentage distributions from the TekScan™ pressure mat. This information can be distributed into point loads as used for this paper's analysis, then using simple beam theory, one should try to develop a model to predict the amount of pallet deflection that could occur as compared to real pallet samples.
4. Evaluate the full pressure distribution across the entire top of the pallet with multiple TekScan™ pressure mats to quantify exactly what is happening across the whole surface.

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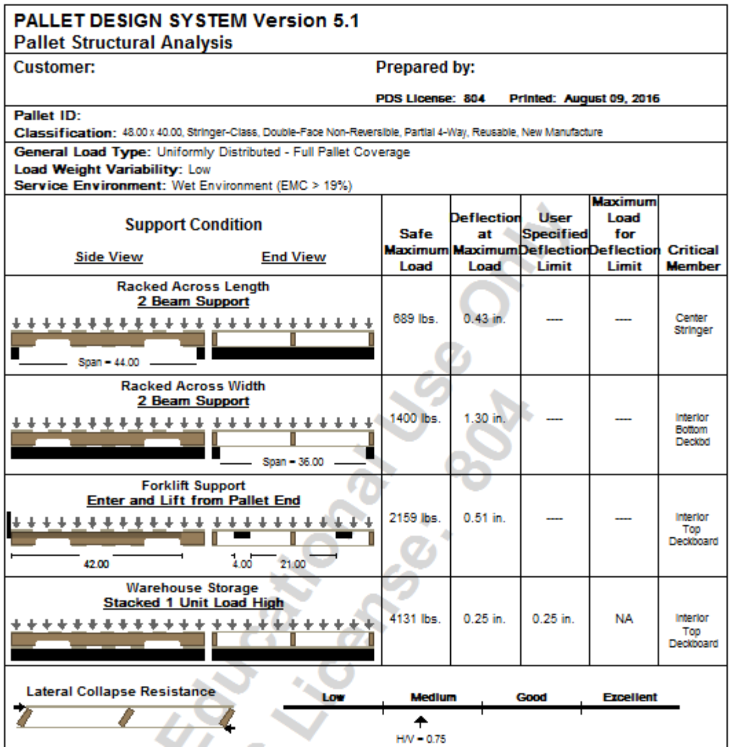
Appendix A: Pallet Specifications



PALLET DESIGN SYSTEM Version 5.1
Pallet Structural Analysis

Customer: **Prepared by:**

PDS License: 804 **Printed: August 09, 2016**

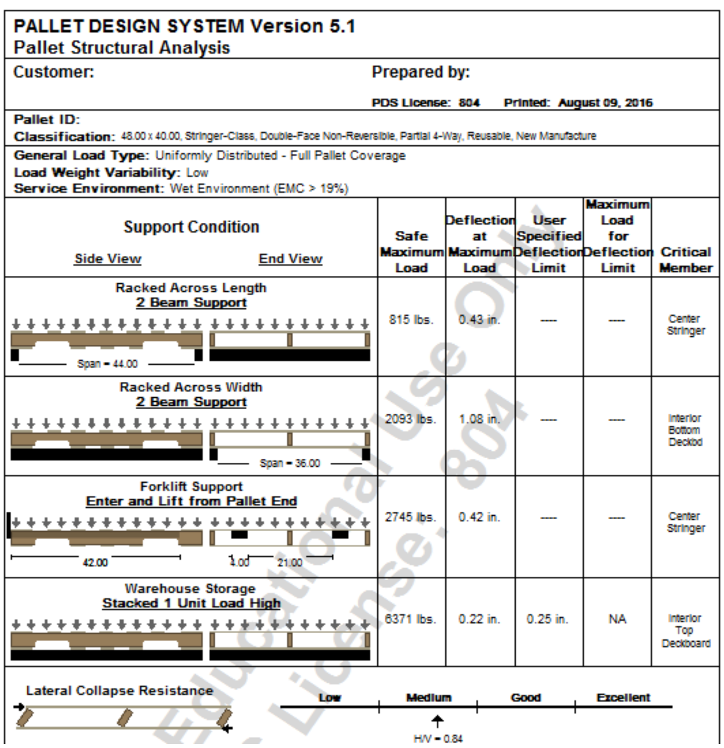
Pallet ID:
Classification: 48.00 x 40.00, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Reusable, New Manufacture

General Load Type: Uniformly Distributed - Full Pallet Coverage
Load Weight Variability: Low
Service Environment: Wet Environment (EMC > 19%)

Support Condition (Side View / End View)	Safe Maximum Load	Deflection at Maximum Load	User Specified Deflection Limit	Maximum Load for Deflection Limit	Critical Member
Racked Across Length, 2 Beam Support (Span = 44.00)	689 lbs.	0.43 in.	----	----	Center Stringer
Racked Across Width, 2 Beam Support (Span = 36.00)	1400 lbs.	1.30 in.	----	----	Interior Bottom Deckbd
Forklift Support, Enter and Lift from Pallet End (42.00; 4.00; 21.00)	2159 lbs.	0.51 in.	----	----	Interior Top Deckboard
Warehouse Storage, Stacked 1 Unit Load High	4131 lbs.	0.25 in.	0.25 in.	NA	Interior Top Deckboard

Lateral Collapse Resistance: Low | Medium | Good | Excellent — H/V = 0.75

Figure 48 Pallet Design System™ structural analysis of the low stiffness pallet used for research.



PALLET DESIGN SYSTEM Version 5.1
Pallet Structural Analysis

Customer: **Prepared by:**

PDS License: 804 **Printed: August 09, 2016**

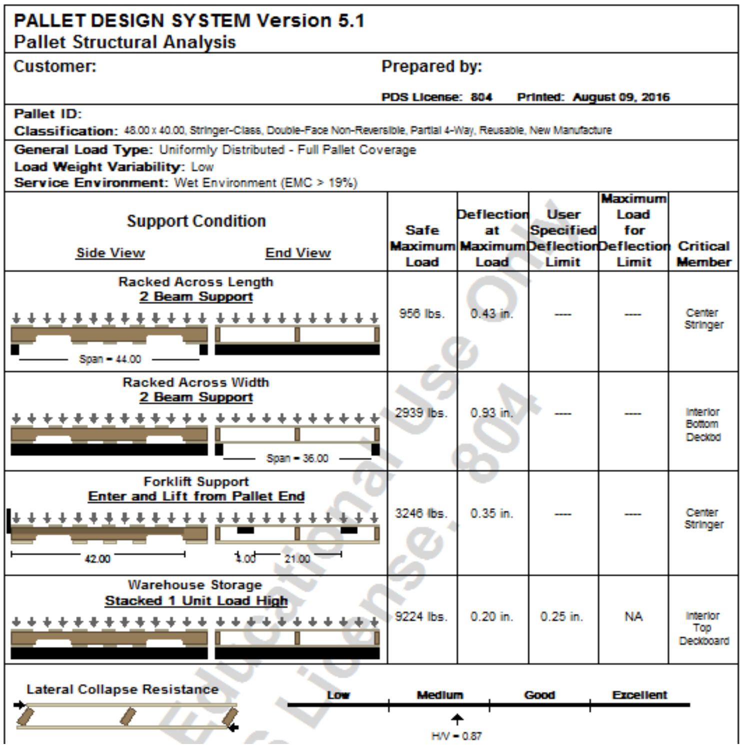
Pallet ID:
Classification: 48.00 x 40.00, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Reusable, New Manufacture

General Load Type: Uniformly Distributed - Full Pallet Coverage
Load Weight Variability: Low
Service Environment: Wet Environment (EMC > 19%)

Support Condition (Side View / End View)	Safe Maximum Load	Deflection at Maximum Load	User Specified Deflection Limit	Maximum Load for Deflection Limit	Critical Member
Racked Across Length, 2 Beam Support (Span = 44.00)	815 lbs.	0.43 in.	----	----	Center Stringer
Racked Across Width, 2 Beam Support (Span = 36.00)	2093 lbs.	1.08 in.	----	----	Interior Bottom Deckbd
Forklift Support, Enter and Lift from Pallet End (42.00; 1.00; 21.00)	2745 lbs.	0.42 in.	----	----	Center Stringer
Warehouse Storage, Stacked 1 Unit Load High	6371 lbs.	0.22 in.	0.25 in.	NA	Interior Top Deckboard

Lateral Collapse Resistance: Low | Medium | Good | Excellent — H/V = 0.84

Figure 49 Pallet Design System™ structural analysis of the medium stiffness pallet used for research.



PALLET DESIGN SYSTEM Version 5.1
Pallet Structural Analysis

Customer: **Prepared by:**

PDS License: 804 **Printed: August 09, 2016**

Pallet ID:
Classification: 48.00 x 40.00, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Reusable, New Manufacture

General Load Type: Uniformly Distributed - Full Pallet Coverage
Load Weight Variability: Low
Service Environment: Wet Environment (EMC > 19%)

Support Condition (Side View / End View)	Safe Maximum Load	Deflection at Maximum Load	User Specified Deflection Limit	Maximum Load for Deflection Limit	Critical Member
Racked Across Length, 2 Beam Support (Span = 44.00)	956 lbs.	0.43 in.	----	----	Center Stringer
Racked Across Width, 2 Beam Support (Span = 36.00)	2939 lbs.	0.93 in.	----	----	Interior Bottom Deckbd
Forklift Support, Enter and Lift from Pallet End (42.00; 1.00; 21.00)	3246 lbs.	0.35 in.	----	----	Center Stringer
Warehouse Storage, Stacked 1 Unit Load High	9224 lbs.	0.20 in.	0.25 in.	NA	Interior Top Deckboard

Lateral Collapse Resistance: Low – Medium – Good – Excellent; H/V = 0.87

Figure 50 Pallet Design System™ structural analysis of the high stiffness pallet used for research.

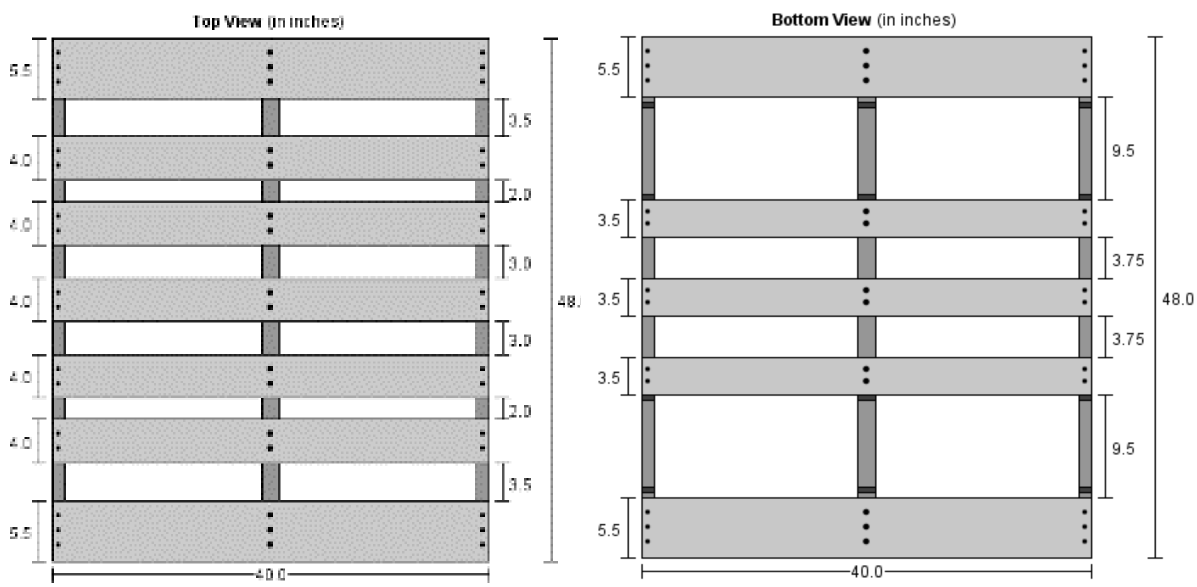


Figure 51 48”x40”, Stringer-Class, Double Face Non-reversible, partial-four way, multiple use pallet.

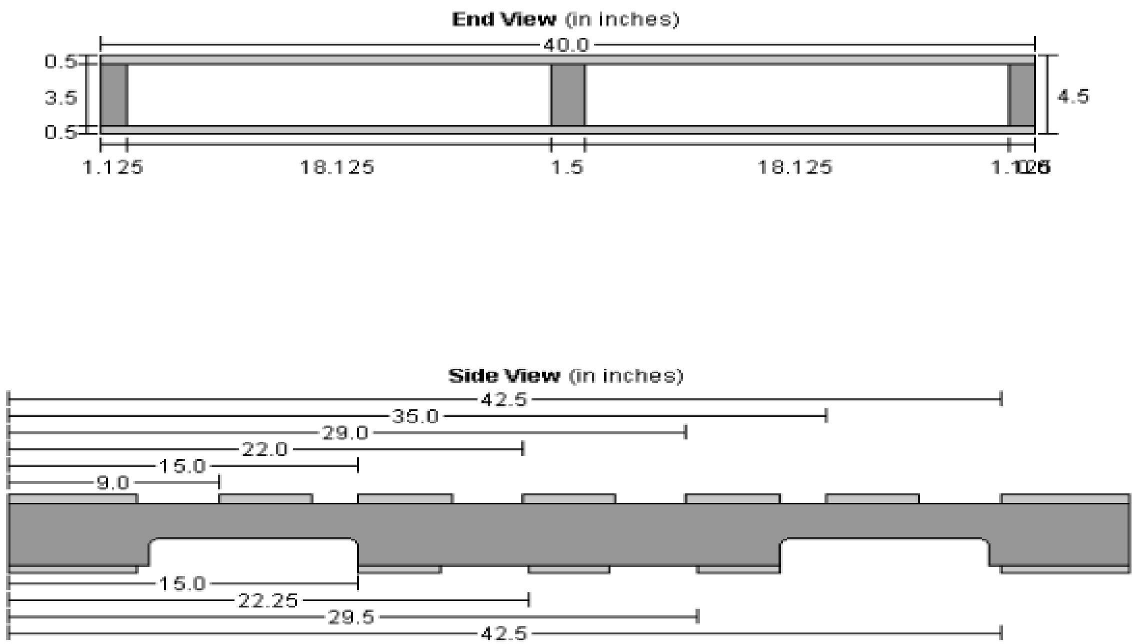


Figure 52 Deckboard placement and stringer placements of the pallet design used for the experimental design.