Measurement of Wood Pallet Performance Subjected to Uniform Loading in Racked, Fork Tine, and Floor Stacked Support Conditions

by

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(ABSTRACT)

Wood pallets are heavily used throughout the United States and the World to transport, store, and protect goods. During a lifecycle, pallets typically experience various stresses from warehouse storage racks, materials handling equipment, and floor stacking situations. The components within the pallet interact to withstand load and impact forces. Every year product damage and human injury/death result from improperly designed pallets, non-reliable packaging systems, and careless materials handling methods.

In use wood pallets are exposed to a variety of loads and support conditions. This research investigates the effect of different pallet designs and support conditions on pallet stiffness. Uniform loads were applied to pallet designs containing thick or thin components and three, four, or five non-notched and notched stringers. The pallets were supported using racked across the length, racked across the width, fork truck tine, and floor stack support conditions. Structural analysis was used to determine the test loads for each pallet bending test. Pallet deflections were measured in specific locations for each bending test.

Pallet test results indicated that heavy duty pallets are 6.5 times stiffer than light duty pallets tested in the racked across width (RAW) support condition. Non-notched pallets tested are 51% stiffer than notched pallets in the racked across length (RAL) support condition. Test results also indicated that a wider fork tine support span decreases average pallet stiffness by 29% and 49% for 4 and 5 stringer pallets, compared to 3 stringer. The heavy duty pallets tested are, on average, 48.3% stiffer than light duty pallets in the fork tine support condition. For the notched fork tine support condition, the

average pallet stiffness decreased by 29% and 3% for four and five stringer pallets, compared to three stringer.

Pallet joints were tested to measure joint stiffness. Joint rotation tests were conducted to determine rotation modulus and joint withdrawal tests were conducted to determine joint withdrawal stiffness. The joint stiffness measurements were used as spring constants in structural analysis based on semi-rigid joint performance. Heavy duty pallet joints were approximately half as stiff (6758 in-lbs/radian) in rotation as light duty pallet joints (12907 in-lbs/radian). Light duty pallet joints were less stiff (44008 lbs/in) in withdrawal than heavy duty pallet joints (57823 in/lbs).

The results from this research were used to compare with results from ANSYS (Version 11) structural model estimates. The average predicted error for all pallet bending tests was 13% (heavy duty) and 3% (light duty).

All pictures included in this document were taken by the author, Braden White, beginning in January of 2007 and ending in December of 2007. All PDS screens scanned into Appendix A were used with the permission of Pallet One, License 253.

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Chapter 1

1.1 Introduction

The packaging and palletization of consumer and industrial products is the largest use of non-fuel wood fiber in the United States. Today, more than 2 billion pallets are in use throughout the U.S., in which 95% are made of either solid wood or wood composites (Ward, 1993) (Modern Materials Handling, 2000). Pallets are used in the transportation and storage of various products in unit load form. The combined masses of individual or bulk products restrained to a pallet are known as a unit load.

Packaging impacts the environment because it is the largest municipal solid waste and consumes vast amounts of energy to produce and transport. Ten years ago close to 72 million tons of solid waste was generated from packaging materials and approximately 17 billion gallons of diesel fuel was consumed to transport unit loads in the United States (EPA, 2002) (ATA, 2000). Human safety is also affected by unit load design. Materials handling related injuries resulted in 25 percent of all occupational injuries in 2003 (Radford University, 2003).

Since the mid 1980s, the use of computer based models have aided the materials handling industry by providing a rational method to design pallets and packaged products in unitized form. Currently, models exist that predict pallet design performance (PDS®) or to identify the best packaging use (TOPPS®) (CAPE®). However, no models for predicting both the geometry and performance of the entire unit load are verified. Development of an analysis model of a pallet is a necessary step toward developing a simplified structural analysis of an entire unit load.

1.2 Problem

The wide use of wood pallets affects the health and safety of humans, annual timber consumption, and the economy. Due to tradition and experience of pallet manufacturers and all other companies that use pallets, often the importance of structural analysis and design are overlooked. Because of this, humans are injured or killed, timber consumption is not moderated, and assets are depleted due to over or under design. In the past, trial and error laboratory testing was the primary approach to solving design related issues.

With the development of structural analysis tools, these issues have been addressed. Both pallet and packaging system deigns have been streamlined to fit customer needs in a safe yet economical manner. However, currently, designers can only develop the pallet design or packaging system independent of one another in a component based methodology. This research is devoted to developing a structural analysis tool capable of analyzing the pallet, packaging system, and entire unit load. The tool would provide the industry with design solutions generated from a systems based approach.

1.3 Cooperative Research Project

A research team was assembled comprised of two groups; Wood/Packaging Science and Engineering Science and Mechanics (ESM). ESM was responsible for developing a structural analysis model using Finite Element Analysis (FEA) and a commercial program ANSYS (version 11) and creating simplified finite element models. Wood/Packaging Science was responsible for developing wood pallet test data that was used to calibrate the FEA. This thesis specifically documents the methodology necessary to develop the pallet test data used for FEA validation. This research and development was privately funded by an outside source.

1.4 Overall Objective

The overall project objective is to develop experimental data for validation of structural analysis models for wood pallets.

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1.5 Scope

This thesis presents techniques used to produce the necessary wood pallet test data for FEA calibration and model validation. A variety of pallet designs and several different support conditions were tested. Two different pallet joint tests were conducted. The scope of the project included:

- Twelve lumber pallets (stringer type), of kiln dried Eucalyptus (*Eucalyptus grandis*).
- Pallets with three, four, and five stringers constructed with lumber of two different thicknesses.
- Notched and non-notched pallets.
- 12 deck boards used in each pallet.
- Pallets with two different deck board thicknesses and two different stringer widths.
- One nail type was used in all pallets.
- Four support Conditions: Racked across the length (RAL), racked across the width (RAW), fork truck tine, and floor stack (top and bottom).
- Load Type: Full uniformly distributed.
- Pallets 1, 4, and 7 are heavy duty 3 stringer designs.
- Pallets 2, 5, and 8 are heavy duty 4 stringer designs.
- Pallets 3, 6, and 9 are heavy duty 5 stringer designs.
- Pallet 10 is a light duty 3 stringer design.
- Pallet 11 is a light duty 4 stringer design.
- Pallet 12 is a light duty 5 stringer design.
- 27 pallet joint rotation samples were tested to determine rotation modulus.
- 24 pallet joint withdrawal samples were tested to determine withdrawal stiffness.

Chapter 2

Literature Review: Pallet Testing

2.1 Introduction

The purpose of this chapter is to provide some of the relevant background information regarding pallet testing used to calibrate structural models. The wood pallet appears to be a simple structure comprised of wood and nails to the untrained eye. In reality, a pallet is a complex structure distributing loads throughout wood components and involves non-linear nail joint actions. Pallet performance can be affected by a number of things including geometries of the pallet and components, species and grade, moisture content, specific gravity, fastener type and nailing patterns, loading characteristics, and materials handling methods.

2.2 Existing Methodology

Loferski (1985) mentioned the methods of investigators looking into both theoretical and empirical pallet design procedures. Heebink (1957, 1959) used the beam theory to calculate the load-carrying capacity of deck boards in the floor stack support condition. It was assumed that pallet loads could be modeled using a point load or uniform load on a simply supported beam. Correction factors were developed by Heebink (1957, 1959) to account for material defects in deck boards which reduced the effective cross-sectional area of clear specimens. Further more, Loferski (1985) also mentioned pallet and skid design procedures developed by Wallin, Stern, and Johnson (1976). Depending on the support and loading conditions, the pallet components were considered to act both individually and in combination as composite beams. Based on the theory of elasticity, two load conditions (distributed and line) and three support conditions (RAL, RAW, and floor stack) were considered for pallet design methodology.

Loferski (1985) mentioned investigators such as Kyokong (1979) and Mulheren (1982) who implemented matrix structural analysis with FORTRAN language and SPACEPAL; space frame analysis of wood pallets.

A long term study was conducted developing a method to insure uniform in-service pallet performance with out regard to the pallet materials. Over 2,000 pallets were subjected to commercial shipping environments and data was collected regarding use, damaged components, condition, and product damage. Results from this study were used to create a computer based model capable of estimating pallet life expectancy, cost-per-use, durability, strength, and stiffness Wallin, Stern, and Johnson (1976).

2.3 Pallet Component Material Properties

In order to understand the mechanical behavior of a wood pallet, the material properties of the lumber used to manufacture the pallet must be known. More specifically, the overall pallet stiffness is a conglomeration of the individual pallet component stiffness or modulus of elasticity (MOE). Polensek (1979) believed that in order to determine the MOE and allowable bending stress for various species of pallet parts, actual pallet parts must be tested rather than clear wood specimens later being adjusted for defects.

The mechanical properties of yellow-poplar pallet material were investigated by Holland (1980). Numerous stringers and deck boards were tested in order to compare with existing grading rules. The mechanical properties of mixed oak pallet parts were studied by Spurlock (1982) in order to determine how defects affect pallet strength and stiffness.

Stern and Wallin (1979) investigated the performance of pallet components subjected to flexural tests. The static stiffness and maximum flexural load-carrying capacity of leading edge stringer/deck board assemblies were determined. Oak/Maple specimen assemblies were found to be stiffer Oak/Cotton wood assemblies.

Measurement

2.4 Pallet Loads and Support Conditions

General load/loading conditions as well as support conditions must be known in order to establish an acceptable pallet design procedure (Loferski 1985). Tanchoco and Agee (1980) investigated unit loads ("composed of one or more bulk items or bulk material arranged on a pallet") by classifying them into three categories; materials that are of uniform geometry that are capable of withstanding load, materials that are capable of withstanding load but require packaging due to non-uniform geometry, and bagged goods capable of compressing into a relatively flat surface. Tanchoco and Agee (1980) stated that unit loads must be designed to be compatible with racking systems, carrier and warehouse dimensions, and product geometry.

In the RAL support case, stringers are stressed as multiple simple beams. Loads are uniformly or non-uniformly distributed with stringers supporting the total pallet load. When notched stringers pallets are RAL, adjustments are used to calculate maximum loads and deflections due to development of stress concentrations at the notch (Collie, 1984). In the RAW support condition, top and bottom deck boards are stressed as a composite beam. Loads are uniformly distributed to the top deck boards. However, because the bottom deck boards typically occupy a smaller surface area, higher stresses are generated in the bottom surface of the pallet from loads transmitted though the center stringer/s (Collie, 1984). When pallets are floor stacked, depending on how many unit loads are in a stack, the top and bottom deck boards are stressed as continuous beams. In this support condition, deck board strength depends on stringer spacing.

Loferski (1985) mentioned further research by Goehring and Wallin (1981) characterizing actual load and support conditions in various materials handling environments. It was stated that static loads on a pallet can be grouped into either uniformly distributed loads, partially concentrated loads, or concentrated line loads. It was also determined that 69% of the pallets used for the study were floor stacked, 10% were RAW, and 21% were RAL. Due to interactions with materials handling equipment, some of the load conditions changed from uniformly distributed to non-uniform (Goehring and Wallin, 1981).

Collie (1984) mentioned research conducted by The Cooperative Pallet Research Program responsible for developing a design procedure for wood stringer-type pallets based on load carrying capacity and durability. The result was a reliability-based design procedure for wood stringer pallets know as Pallet Design System (PDS). To insure reliability and safety in the designed pallet, an accurate load-support model is required. Stacked and racked support conditions under various loads could be analyzed. Key areas of examination included load distributions between pallets stacked on one another and the phenomenon known as load bridging. Load bridging occurs when the unit load is stiff in relation to the pallet. Pallet deflection can cause a semi-rigid load to bridge between supports, such as stiff boxes or bricks/cinder blocks. In such cases the assumption of a uniformly distributed load may be unrealistic, resulting in erroneous predictions of pallet deflection and load capacity (Loferski, 1985).

Collie (1984) found that neither the pallet stiffness nor the load type or configuration significantly affected load distribution. The proportion of load distribution to the top deck of pallets stacked 1, 2, or 3 high was 100%, 80%, and 66% respectively. The remaining load is transferred through the stringers directly to the floor and therefore does not contribute to the bending stress of the top deck boards of the bottom pallet in a stack (Loferski, 1985). Collie also stated that pallets of low stiffness experience significant load bridging in either RAL or RAW support conditions, rendering the pallet from exhibiting deflections from a true uniform load.

A rational analysis procedure for designing wood stringer pallets for use in warehouse storage racks was developed for manufacturers and pallet users and is part of a computerized automatic design and analysis program called the Pallet Design System. Semi-rigid nail joint were modeled as spring elements. Pallets with 2, 3, 4, or 5 stringers and up to 15 deck boards can be analyzed with distributed or concentrated loads. The strength and stiffness of experimental pallets were compared to predicted values and showed good agreement (Loferski and McLain, 1987).

2.5 Further Investigations of Stringer Pallet Stiffness

A study was conducted in 1976 which investigated the stiffness and flexural strength of hardwood pallets of different design and moisture content. Test loads from 4,200 pounds to 12,800 pounds were applied and deflections were recorded in various locations at 200 pound loading increments. The test support conditions were not specified, but deflections were measured in the center and either end of each pallet specimen. The data was not recommended for field conditions due to the lack of testing replications (Stern, Norris, 1976).

Another study investigated the stiffness and rigidity of 22 southern hardwood GMA (Grocery Manufacturer Association) pallets. All pallets were manufactured with green lumber and hardened-steel helically threaded nails. The findings indicate that under the prevailing test conditions, deflections at the pallet sides are less than deflection at the ends when subjected to concentrated loads at the center of each pallet. Class 2 (lighter) species were found to be more rigid during corner drop testing. The stiffness of the tested pallets can be predicted if the flexural MOE of the wood species are known (Stern, Norris, 1976).

2.6 Notched Pallet Component Testing

Existing research investigatig notched pallet performance is limited in scope. However, a study was conducted by Zalph (1989) where the strength of notched wood beams was predicted. Hoop stress is defined for rotationally-symmetric objects being the result of forces acting circumferentially (perpendicular both to the axis and to the radius of the object) (Wikipedia.com). A critical fillet hoop stress model was derived to predict the capacity of a simply supported wood beam with a notch on the tension face. The belief was that cracking initiates when the hoop stress tangent to the free surface of a round-cornered notch exceeds a critical value (Zalph, 1989). Finite element modeling was used to explore various effects of notch locations, notch geometries, beam sizes, loading configurations, and material properties.

Zalph (1989) tested a variety of hardwood and softwood species in both green and kiln dried conditions. Both notched and non-notched beams were tested for necessary comparisons. Preliminary test results showed the effective fillet radius to be material dependent and beam depth dependence was suggested as well. SG and cross-grain tensile strength were strongly related to the notched beam strength parameter. A regression equation was developed to estimate the strength parameter for other solid wood materials (Zalph, 1989).

Chapter 3

Wood Pallet Racking Tests

3.1 Introduction

The testing of pallets is discussed in chapter 3. Descriptions of the materials used as well as experimental procedures are explained. In the development of custom structural analysis models of wood pallets, it is necessary to develop and verify an analysis model. The analysis model was developed using ANSYS (Version 11). Pallet parts were tested non-destructively in bending prior to test pallet assembly. This was done to determine modulus of elasticity of the parts for input into the analysis model. Pallet component tests are described followed by assembly methods for the different pallet designs. The following pallet test support conditions are described: racked-across-length, racked-across-width, forktine, and floor-stack. These are the four most common conditions of pallet use.

Before each of the 12 test pallets were assembled, each component was tested to determine the MOE. Four pallets of each design (three, four, and five stringer) were assembled. Nine of the pallets were "heavy duty," meaning they were assembled using one inch thick deck boards and one and three quarter inch wide stringers. The remaining three pallets were light duty meaning they were assembled using one half inch thick deck boards and one and one half inch wide stringers. The nine heavy duty pallets were tested nondestructively using RAL, RAW, and fork tine support conditions. The three light duty pallets were tested non-destructively using RAW, fork tine, top deck floor stack, and bottom deck floor stack support conditions. The light duty pallets were not tested using the RAL support condition to avoid repetitive test results. The critical members in RAL test support conditions are the stringers and the difference in stringer width between heavy and light duty pallet designs was only one quarter of one inch. Only the light duty pallets were tested using the top and bottom floor stack support conditions due to greater flexibility.

The nine heavy duty pallets were first tested without notches and then with notches cut into the bottom surface of the stringers in specific locations. Notches are cut into pallet stringers in order to allow partial four-way access with a fork truck. However, partial four-way access does not allow four-way access with a pallet jack or hand truck.

Fifty-one pallet joints were manufactured using the same materials and assembly methods as the actual test pallets. Twenty-seven of the pallets were tested to determine the joint rotation modulus and twenty-four were tested to determine the joint withdrawal stiffness. Both heavy duty and light duty pallet joints were tested in joint rotation and joint withdrawal. The joint tests were conducted to estimate joint stiffness properties of the overall pallet stiffness when subjected to loads using various support conditions.

3.2 Objectives

The research objectives are:

- Measure pallet stiffness under uniform load in rack, stack, and fork tine support conditions.
- To measure nail joint stiffness (rotational and withdrawal) for use in modeling pallet deformation under load.

3.3 Materials and Equipment

Section 3.3 contains descriptions of all materials and equipment used for this research project.

Wood Species: Myrtaceae, *Eucalyptus grandis*.

Grain Orientation: Deck boards tested flat and stringers tested on edge with the load applied perpendicular to grain.

Moisture Content, Specific Gravity, Grade: Kiln Dry 19%, 0.45, Select

Number of Components: (Nine heavy duty pallets and three light duty pallets.)

Table 1: Number of components for heavy duty and light duty pallets.

Heavy Duty Pallets				
Component	3(3-Stringer)	3(4-Stringer)	3(5-Stringer)	Total
Interior Boards	24	24	24	72
Lead Boards	12	12	12	36
Stringers	9	12	15	36
Light Duty Pallets				
Component	1(3-Stringer)	1(4-Stringer)	1(5-Stringer)	Total
Interior Boards	8	8	8	24
Lead Boards	4	4	4	12
Stringers	3	4	5	12

Component Dimensions:

Heavy Duty Pallets:

Lead boards: 39.5 inches long, 5.813 inches wide, 1 inch thick

Interior boards: 39.5 inches long, 3.938 inches wide, 1 inch thick

Stringers: 47.5 inches long, 1.75 inches wide, 3.875 inch high

Light Duty Pallets:

Lead boards: 39.5 inches long, 5.813 inches wide, 0.5 inch thick

Interior boards: 39.5 inches long, 3.938 inches wide, 0.5 inch thick

Stringers: 47.5 inches long, 1.50 inches wide, 3.875 inch high

Nail Type:

Helically threaded 2.25 inch long 0.115 inch wire diameter, non-hardened, blunt point, counter-sunk head.

Test Machine:

810 MTS Servo-hydraulic with 1000 pound Interface load cell model #1210A-1K-B.

MTS 10 GL Electrical-mechanical with 10,000 pound MTS load cell model # 27-00112.

Tinius Olsen:

Electric/Mechanical compression machine.

4 x 5 thousand pound BLH electronic load cells model # U3SBL.

Linear Variable Differential Transducer (LVDT):

One inch Schaevitz LVDT Model 100HR-DC (working distance +/- 1in).

Two, two inch Schaevitz LVDT Model 200HR-DC (working distance +/- 1in).

Two Trans-tek LVDT's model #0351-0000 (+/-0.1in).

Rotary Potentiometer (string pot):

3x UniMeasure 5inch model P510-5-S3 (working distance +/- 0.15in).

3.4 Experimental Procedures for Heavy Duty Pallets

3.4.1 Pallet Component Testing

It was necessary to determine modulus of elasticity (MOE) for all deck board and stringer components. MOE is the input required for a finite element analysis (FEA) model to predict the stiffness of the pallet structure.

To determine the MOE, each pallet component was measured using single point bending tests on the Material Test System (MTS). Test supports had flat surfaces that were capable of pivoting and sliding to reduce friction. The load applicator used a load head capable of applying a load at the center line to the samples allowing them to bend freely. Both halves of each deck board were tested separately using 19 inch support spans. All stringers were tested using a 46 inch support span. Each deck board was tested twice, resulting in two MOE values for each sample. This was done to measure deck board stiffness in the span between stringers in the pallet.

A 1000 pound load cell was used for all tests. Deflection measurements were recorded using a one inch Schaevitz LVDT (model 100HR-DC) mounted to a yoke. Two different yokes were needed for the two different test spans. Wood screws were used to hang the yoke from the samples and an S-hook attached to a woven filament line was used to hang the LVDT rod as shown in Figure 1. A schematic figure of the MOE test set up for a stringer is shown in Figure 2. A photograph of a single point bending test for a deck board can be found in Figure 1 of Appendix A.

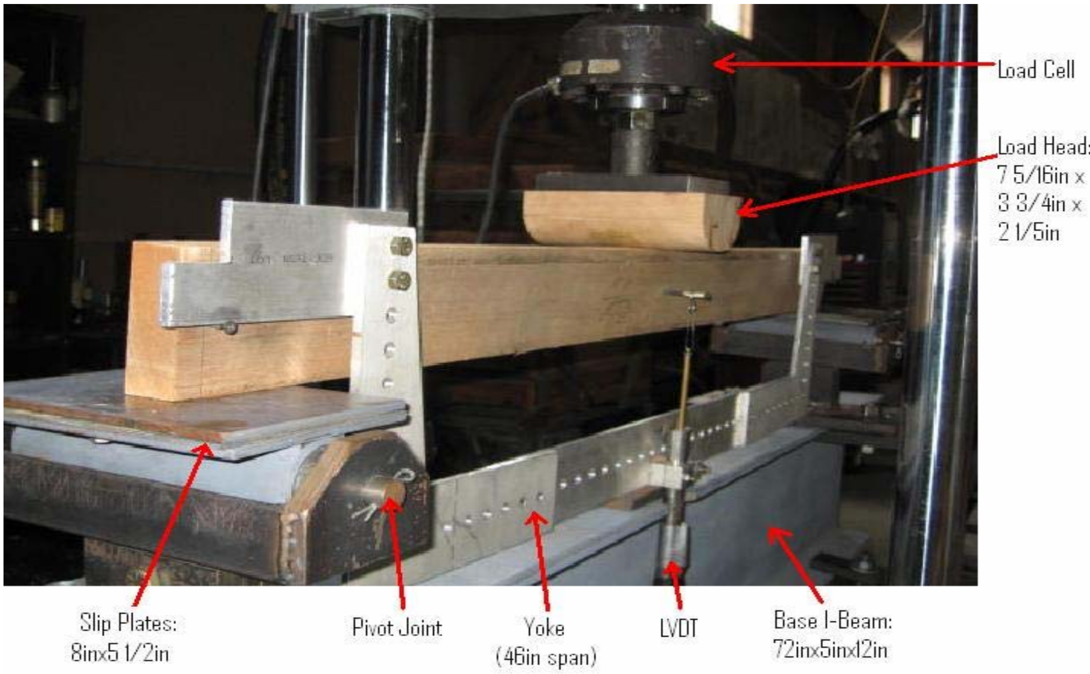

Figure 1. Stringer MOE test setup.

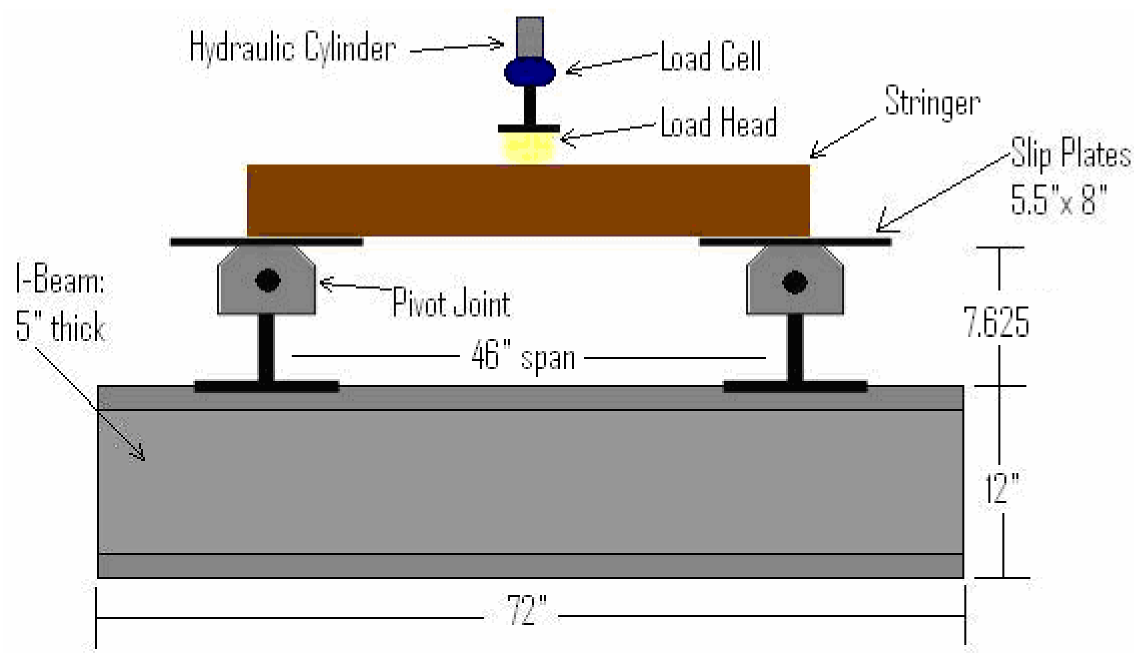

Figure 2: Schematic figure showing the MOE test set up for a stringer.

Preliminary samples were tested to verify the test set-up. Prior to testing, each board was measured for length, width, and thickness with a micrometer (0.001 inch accuracy). A 500 pound load was applied to all deck boards and a 1000 pound load was applied to all stringers in order to obtain adequate deflections for stiffness calculations. Load-deflection curves were recorded simultaneously on a computer data acquisition system (LabTech,).

The following equation was used to calculate MOE:

$$MOE = \frac{P\ell^3}{48\,\Delta\,I} \qquad [1]$$

where:

P = load (pounds)

Δ = deflection (inches)

ℓ = span (inches)

I = (b*d^3)/12   where b = width and d = depth

MOE values for all components can be found in Table 1 of Appendix B.

Average MOE values are listed in Table 2:

Table 2: Average MOE values for pallet parts for heavy duty pallets.

Component	MOE (psi)	COV (%)
Interior Boards	2,200,000	15.0
Lead Boards	1,800,000	12.4
Stringers	1,600,000	10.7

3.4.2 Pallet Assembly

Nine pallets (three pallets of each of the three designs) were constructed from the tested components. Pallets were assembled using a two-way, stringer-class, double face non-reversible footprint. From that footprint, three, four, and five stringer designs were manufactured with very similar overall length, width, and component dimensions. After the pallets were tested nondestructively in various support conditions, the stringers were notched, thus changing the design to a partial four-way and each pallet was retested. Nondestructive testing (flexing) determines the stiffness of the pallets where destructive testing (testing to failure) would determine the strength of the pallet. For this research, only the stiffness of the pallet was needed, therefore only nondestructive testing was conducted. Design details and structural analysis can be found in Appendix A, figures 2 through 7, courtesy of PDS (License 253). Figure 3 shows schematics of the different pallet designs.

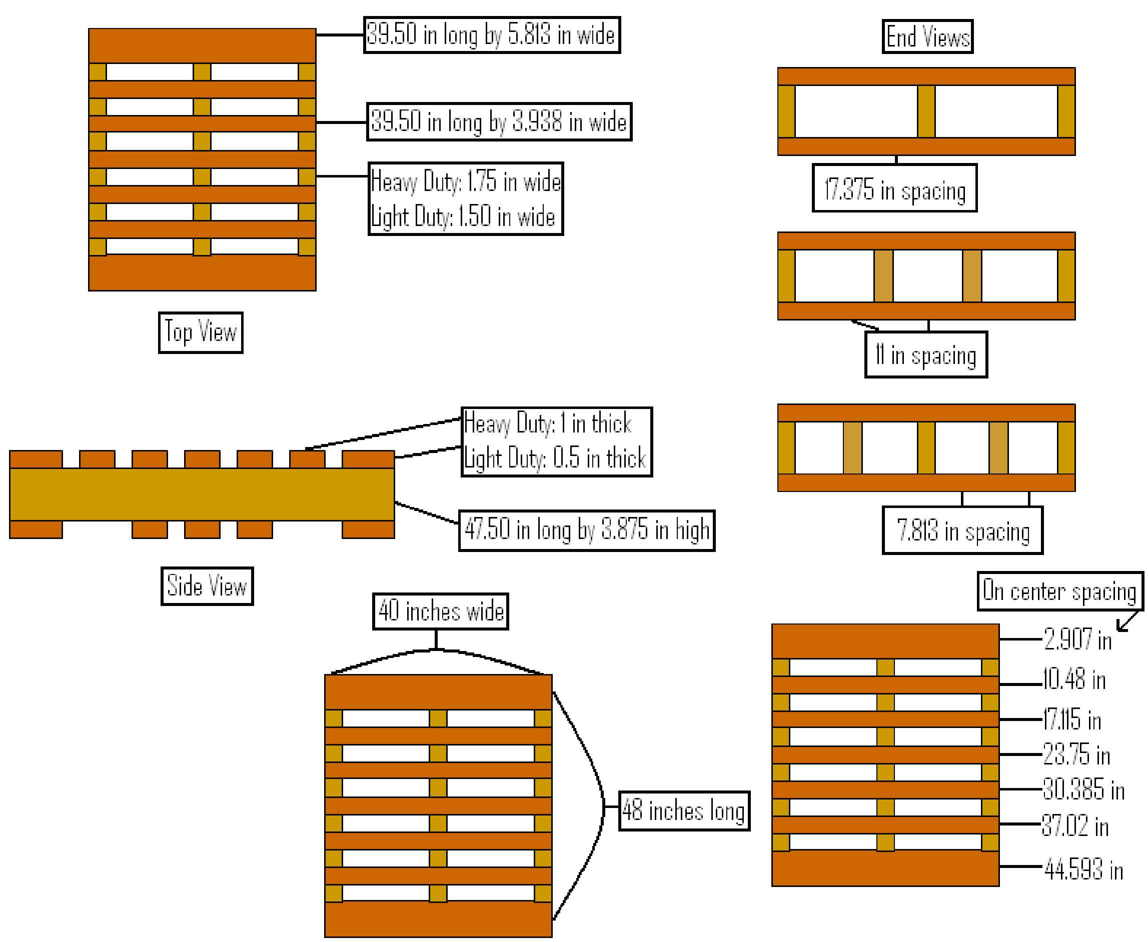

Figure 3: Schematic showing the pallet designes.

All pallet components were ranked according to MOE and separated into three groups: high, medium and low stiffness. From each group, a three, four, and five stringer pallet was assembled. Pallet #1 contained the least stiff components and pallet #9 contained the stiffest components. Pallet component grouping can be found in Table 3.

Table 3: Pallet Component Grouping

Pallet Component Grouping		
Pallet #	# of Stringers	MOE
1	3	Lowest
4	4	
7	5	
2	3	
5	4	
8	5	
3	3	
6	4	
9	5	Highest

An assembly template (jig) was made from 48 inch by 1.5 inch plywood strips screwed to a four foot by five foot OSB sheet. By positioning the strips, all three pallet designs could be assembled with stringers correctly spaced. Figure 8 in Appendix A illustrates the jig for three and four stringer pallet assembly. Stringer spacing for each of the pallet designs are shown below in Figure 4.

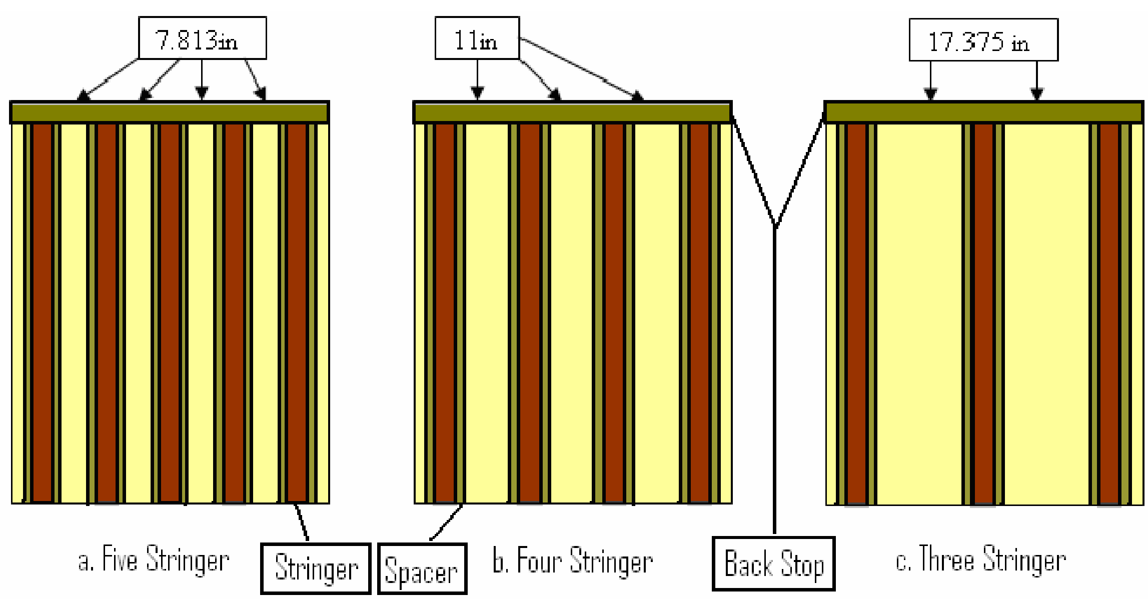

Figure 4: Pallet Jig Spacing Design

Pallet assembly began with the positioning of the stringers and top-deck boards on the jig. Stringers were slid between the appropriate plywood strips and lead boards and interior boards were laid across the top surface. Top-deck lead boards were nailed to both ends of the stringer surfaces flush with the ends, followed by the interior top-deck boards. Figure 9 in Appendix A illustrates a completed top deck assembly. The interior boards were spaced by using 2 11/16 inch long wooden blocks that were 1⅞ inches wide by 1 ¾ inches tall, providing even deck board spacing. Nailing jigs were made for lead board (three nails per joint) and interior board (two nails per joint) joint connections. This was done to ensure consistent nailing patterns for all pallet joints. The nail jig was placed on top of each joint and a felt-tip marker was used to mark the intended nail locations through ⅛ inch holes. A diagram of the nailing jigs is shown below in Figure 5.

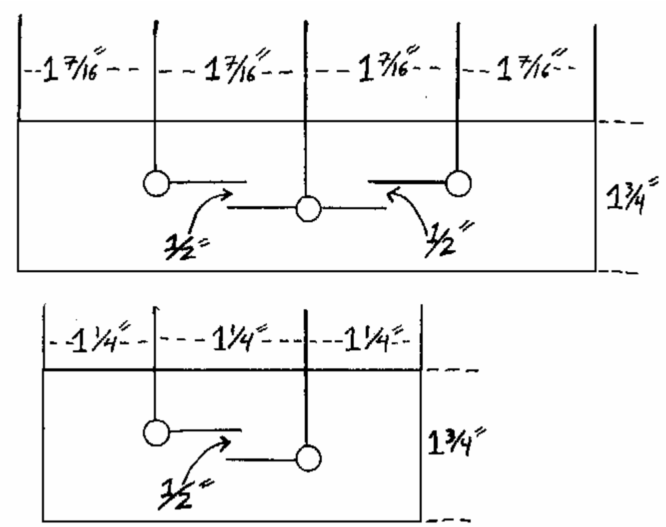

Figure 5: Nailing Jigs

A drill was then used to pre-drill holes into the nail locations in order to avoid wood splitting as the nails were driven with a hand-held hammer. The depth of pre-drilling was 2¼ inches to comply with the nail length. The drill bit diameter (.100 in) was 77% of the nail thread diameter (.130 in) to eliminate wood splitting and ease nail driving. All nails were driven until the heads were flush with the surface of the deck boards. The fastener quality assessment (FQA) for the nail used in this research can be found in Figures 2 through 7 in Appendix A.

Each pallet was turned over after the top deck assembly was complete, to nail the bottom deck boards. Lead boards were positioned and nailed flush to the stringers. Center line marks were made on the stringers to position the center interior board and the spacer blocks were used to locate the other two interior boards. Three interior boards were used for the bottom surface of all nine pallets to allow adequate spacing for cutting notches in the stringers.

3.4.3 Test Procedures for Racked Across Length (RAL) Pallet Bending Tests

Warehouse storage racks subject pallets supporting unitized loads to various racking conditions. Pallets that are racked perpendicular to the stringers are called racked across length (RAL). In this situation, the stringers are supporting the load and are stressed in bending. It is not common for non-notched pallets to be racked in this fashion because fork trucks cannot enter from the stringer side. However, for this study it is important to understand how non-notched stringer pallets perform in RAL situations.

Prior to assembling the RAL test set-up, a 50 pound weight was placed on each of the four load cells in order to verify load measurement accuracy. C-clamps were used to secure two I-beams, modified with welded pipes to perpendicular base I-beams. Each pallet was then placed into the test machine and 60 inch by 2-inch by ¼ inch steel sway bars were slid in between the bottom deck lead boards and the supports. Sway bars reduce friction between the lead boards and the supports, allowing the pallet to deflect freely. The pallet was then centered relative to the supports and a 56 inch by 48 inch rubber dunage bag (air bag) was placed between the pallet and the top platen of the Tinius-Olsen compression machine. A computer controlled air solenoid monitors the air compressor which fills the bag. Because the steel platen was fixed (stationary) in place eight inches above the surface of each specimen, the bag was able to apply a uniform load to the pallets with total coverage. Three different string pots were used to measure pallet deflections. Each was a UniMeasure, model P510-5-S3, 5-inch device. The pots were located underneath the pallet. String pot locations are shown in Figure 6.

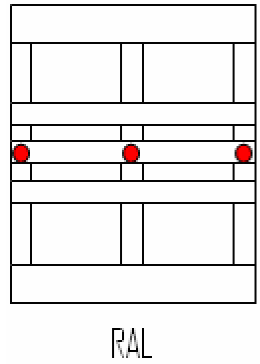

Figure 6: Schematic showing bottom view of string pot locations for RAL bending tests.

Eye-hooks were screwed into each stringer location in order to attach the string pots. Magnets were used to restrain the string pot housing to the base of the compression machine. The string pots were hung vertically to avoid unwanted string angles causing improper deflection measurements. The RAL test set up is shown below in Figure 7.

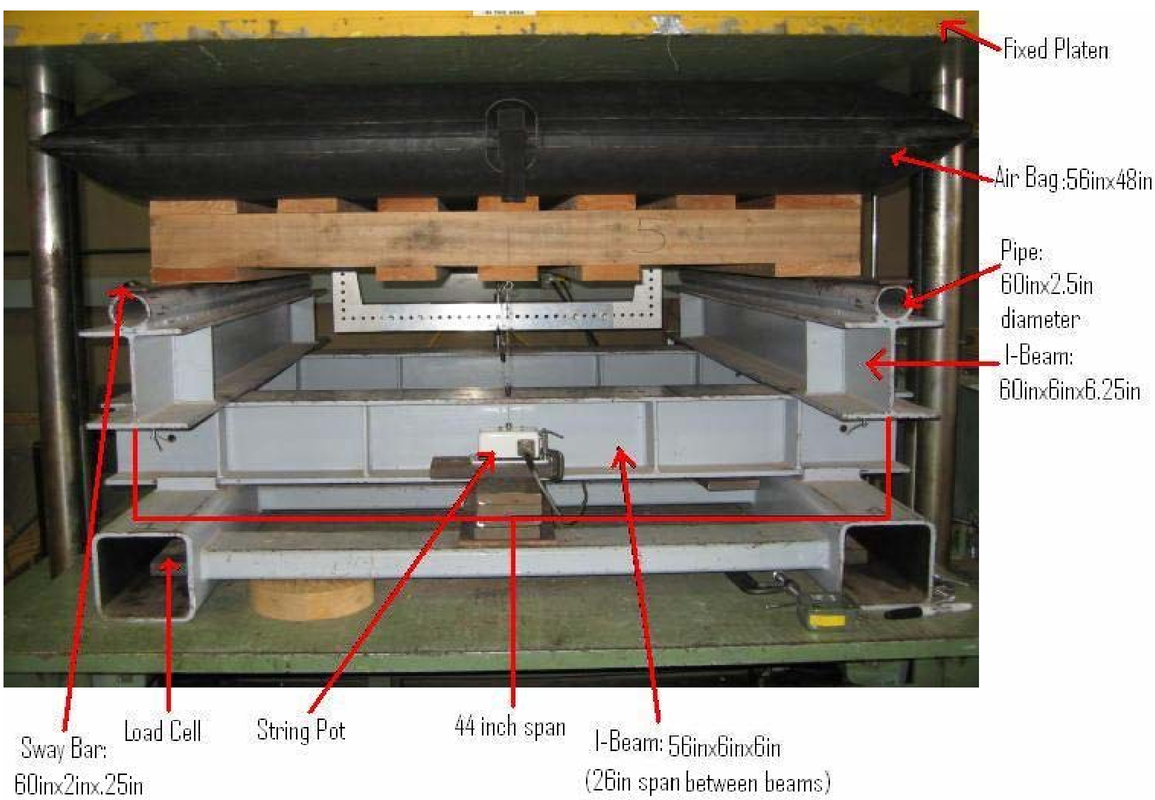

Figure 7: Photograph of the pallet bending test spanning the pallet length.

Wood screws were used to suspend an adjustable aluminum yoke from the side of the pallet. One screw was located in the geometric center of the stringer face and the other two were 44 inches apart on the same plane as the center screw. These locations allowed the yoke to be supported directly over the test supports. The yoke was used to attach an LVDT relative to the pallet stringer neutral axis in order to record deflection. Diagrams of the yoke can be found in Appendix A, Figure 11. Because the string pots are mounted to the base of the compression tester, they measured pallet deflection as well as machine compliances. The LVDT was used to measure the overall compliance of the test setup. This was done by subtracting the LVDT measurement from the string pot measurement yielding the total amount of machine compliance caused by settlement in the supports and deflection of the steel support beams. The support deflection was then subtracted from the original string pot measurements to compute the actual pallet deflection at each string pot location. The output from all three string pots and the LVDT were zeroed (zero voltage) prior to testing. Figure 8 demonstrates the compliance for a RAL bending test.

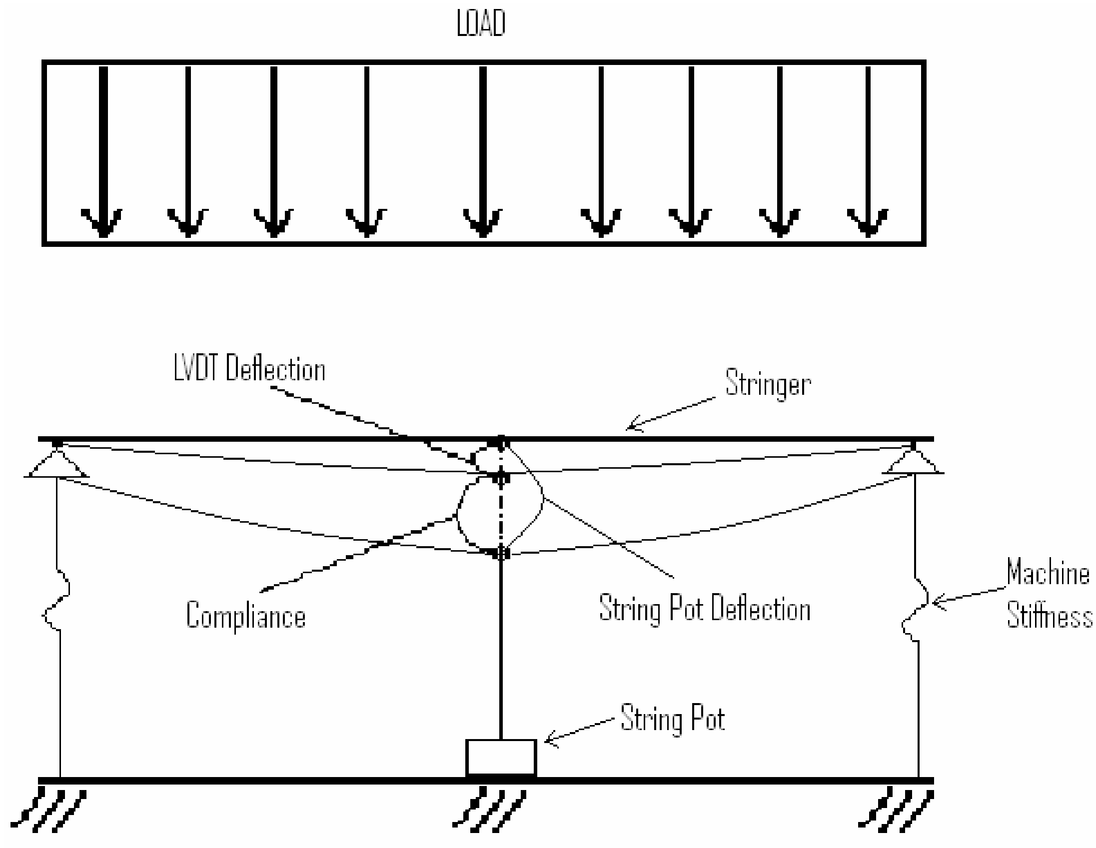

Figure 8: Diagram demonstrating compliance for a RAL bending test.

For RAL and RAW tests, the LVDT deflection is assumed to be the actual deflection of the pallet. However, string pots were used to measure pallet deflections due to difficulty of attaching a yoke to the center of the pallet. The string pot deflections had offsets resulting from test machine compliance that were taken into account by using the following equations:

$$\text{RAL and RAW} = \Delta_{compliance} = \Delta_{pot} - \Delta_{LVDT} \quad \therefore \quad \Delta_{actual} = \Delta_{pot} - \Delta_{compliance} \qquad [2]$$

$$\text{Fork Tine} = \Delta_{actual} = \Delta_{pot} - \Delta_{LVDT} \qquad [3]$$

Testing profiles were created using a computer program to specify how much load was to be applied for a specified duration to each pallet. Each profile had six data columns with three different slots to specify the starting load, ending load, and ramp-to-load time. Test profiles also used a three cycle series in order to flex the joints. This provided an understanding of how stiff the joints would be in an actual handling environment. All ramp-to-load time durations were six minutes, other than the last which was seven minutes to fully deflate the rubber bag enough to remove it for the next pallet bending test.

Test load levels were determined from the pallet design analysis outputs found in Appendix A, Figures 2 through 7. However, the actual racking loads used were 90% of the design loads from the analysis. This was done to maintain the load in the elastic region of response to reduce the possibility of damaging a pallet throughout the testing procedure. The goal of each test was to investigate the stiffness of the different pallets through non-destructive testing. The test loads for the heavy duty pallets are in Table 4.

Table 4: Test loads for heavy duty pallet bending tests.

Heavy Duty Pallet Racking Loads (lbs)					
Pallet Design	RAL	RAW	Forktine	Top Floor	Bottom Floor
3-Stringer	4951	4535	10480	NA	NA
4-Stringer	7491	5910	10480	NA	NA
5-Stringer	9326	5530	10480	NA	NA

3.4.4 Test Procedures for Racking Across Width (RAW) Pallet Bending Tests

In contrast to RAL, the racked across width condition takes place when pallets are racked perpendicular to the deck boards. In this situation, the deck boards span the supports and are stressed in bending. RAW is the most common way to support 2-way (non-notched) pallets in a rack system.

The test set-up was changed to simulate RAW using the same compression machine. The support span was 36 inches. Because the pallet was placed into the tester with the deck boards perpendicular to the supports, the air bag was rotated 90 degrees before it was placed on top of the pallet. Aside from fine adjustments, the string pots remained in the same locations relative to the base of the test machine. In RAW testing, the string pots were arranged to measure deflection from the bottom deck boards directly under the center stringer. String pot locations for RAW testing are shown in Figure 9.

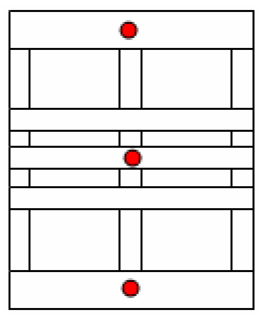

Figure 9: Schematic showing bottom view of string pot locations for RAW bending tests.

The RAD test set up is shown below in Figure 10.

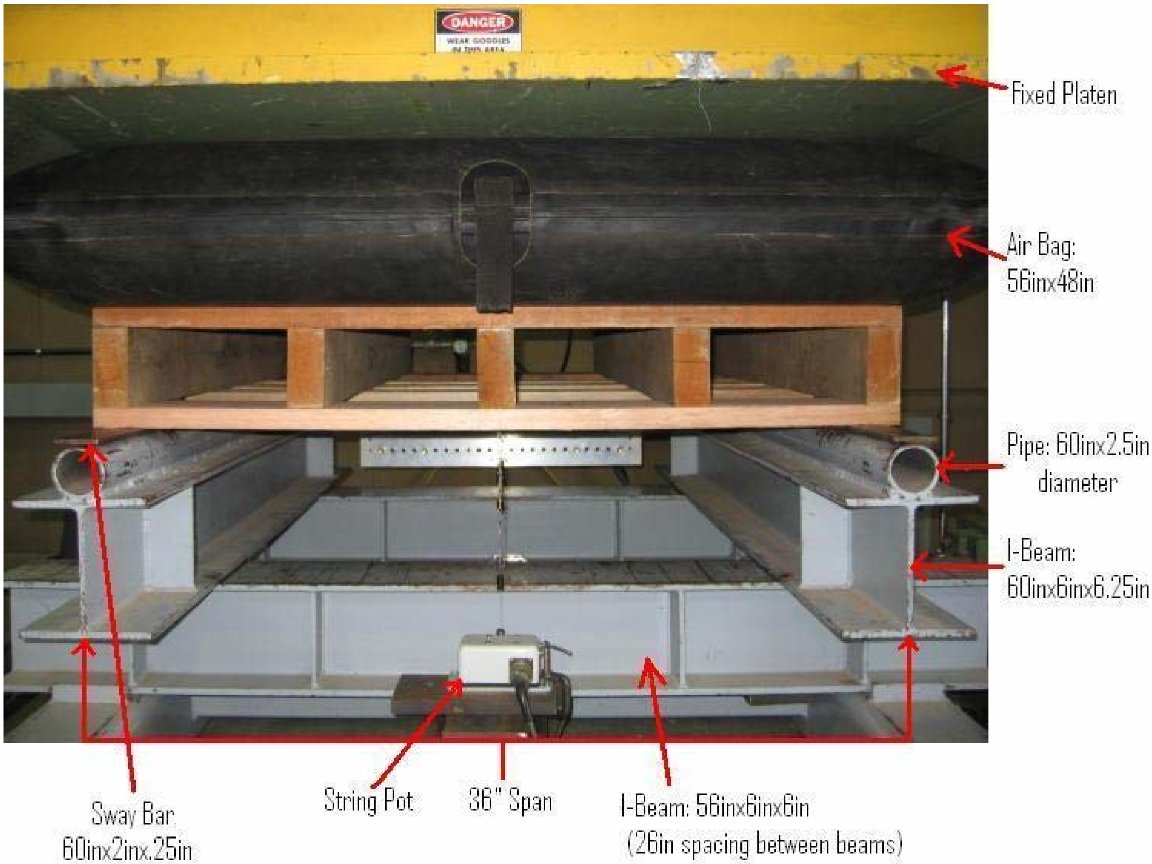

Figure 10: Photograph of the pallet bending test spanning pallet width.

Wood screws were used to attach the yoke and LVDT to the pallet. The screws for the yoke were located on the edge of the bottom lead board. The outer two screws were 36 inches apart located directly over the supports with the third screw was located in the center edge of the lead board. It was necessary to adjust the yoke length in order to attach the LVDT for the 36 inch support span. Figure 13 in Appendix A shows how the LVDT was attached for RAW testing.

The output of all string pots and the LVDT were zeroed prior to testing. The fixed platen was positioned eight inches above the top surface of the pallet with the air bag centered in between the platen and the pallet. A new testing profile was created for RAW testing. The test loads were determined from structural analysis using PDS® and 90% of those design loads were used in the actual testing profiles. Refer to Table 4 for the RAW test loads used in this study.

3.4.5 Test Procedures for Fork Tine Support Pallet Bending Tests

Another critical support condition for pallets occurs when they are transported by fork trucks. Fork trucks are used to load, unload, and transport pallet loads or unit loads. Even though pallets are not stored on fork trucks, they still must withstand stresses when in transit. Fork trucks move pallets with steel fork tines that are typically 42 inches long, 4 inches wide, and 1.5 inches thick. The spacing between the fork tines depends on the dimensions of the pallet. 22 inch spacing is typical for 48 inch by 40 inch 2-way or partial 4-way stringer pallets. For this study, non-notched pallets were supported by the top deck boards during fork tine testing.

Because existing structural analysis programs do not provide design loads for fork tine support, a non-notched three stringer prototype pallet was tested in both RAW and fork tine support conditions. Data from these tests were combined with data from a three stringer RAW test to form a proportional relationship between pallets tested using different supports. This proportion was used to determine appropriate test loads for the fork tine tests. The prototype pallet was tested RAW and then supported by the fork tines in order to determine appropriate test loads needed to bend the pallet a total of 0.2 inches. Once this was complete data from a three stringer RAW test was used to compute the load that would produce 0.2 inch deflection. An example calculation for computing fork tine test load is given below.

$$\frac{RAD}{ForkTine} = \frac{RAD}{x} \quad : \quad \frac{700lbs}{2108lbs} = \frac{3480lbs}{x} \quad : \quad \text{x = 10480 lbs} \qquad [4]$$

Where:

RAD = RAD test load (prototype pallet): 700 lbs

Fork Tine = Fork tine test load (prototype pallet): 2108 lbs

RAD = RAD test load (test pallet): 3480 lbs

x = Fork tine test load (test pallet): 10480 lbs

Fork tine support test loads for three, four, and five stringer pallets were identical because the deck boards are the critical member and all designs have the same number and size deck boards. The fork tine support test loads can be found in Table 4.

Significant changes were made to the test setup in order to simulate the fork tine support. The large modified I-beams used for RAL and RAW testing were replaced with four different I-beams (60inx4inx4.25in). All four I-beams were used to create a box-beam in order to support the fork tines. Two of the I-beams were placed on top perpendicular to the base beams which were located on top of the four load cells. The other two I-beams were placed on top and perpendicular to the first two I-beams, completing the box-beam frame. C-clamps were used to clamp the four I-beams together. Fork times were simulated using two steel strips (54inx4inx0.312in) screwed on top of two solid steel square bars (52inx2inx2in). Each pallet was put into the test setup before the fork tines were slid into place. The fork tine support test setup is shown below in Figure 11.

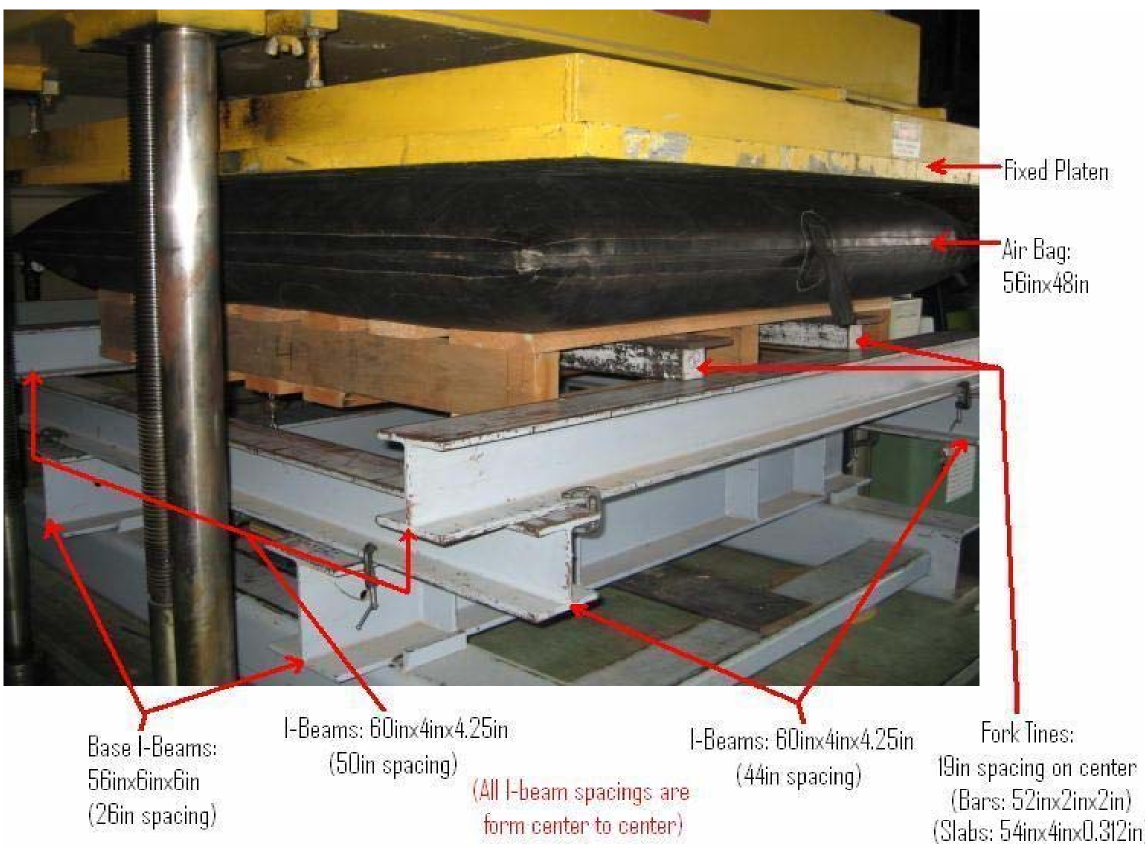

Figure 11: Photograph of the fork tine support test spanning pallet width.

A schematic of the fork tine support test set up is shown in Figure 12.

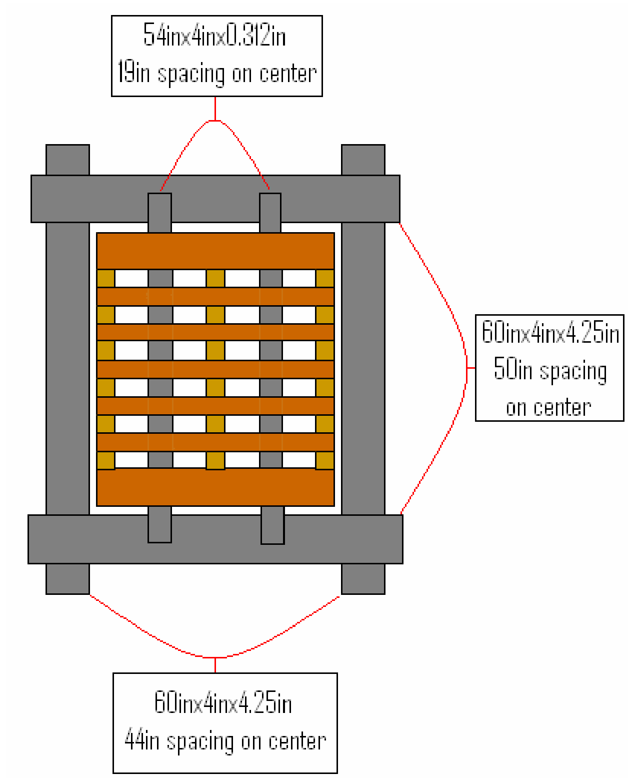

Figure 12: Schematic showing aerial view of the fork tine support test set up.

The fork tine spans were adjusted for the different pallet designs. Three, four, and five stringer pallets were tested using 19 inch, 24¾ inch, and 28⅛ inch fork tine spacing respectively.

String pot locations for fork tine support testing are shown in Figure 13.

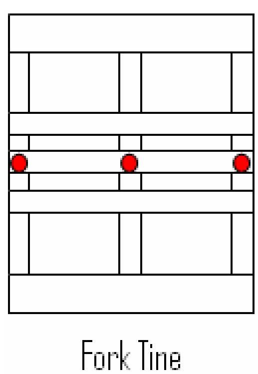

Figure 13: Schematic showing bottom view of string pot locations for fork tine support bending tests.

The yoke could not be used to suspend the LVDT, because of the limited amount of space in the test setup. Therefore, it was not possible to measure pure pallet deflection with the LVDT. Consequently, the yoke was replaced with a lab clamp stand. The stand held the LVDT, allowing it to measure the amount of deflection from the fork tine surface in reference to the base of the compression machine. A C-clamp was clamped to the fork tine between the pallet and the top I-beam. String line was looped from the C-clamp in order to hang the LVDT rod. The lab clamp stand and LVDT are shown in Figure 14 of Appendix A.

Similar to RAL and RAW tests, the string pots measured both the deflection of the pallet as well as the settlement in the test setup for fork tine support tests. The LVDT measured deflection from the fork tine surface relative to the base of the test machine. In this case, the LVDT measured the deflection of the steel bars in the test setup. To determine pallet deflection, the LVDT measurements were subtracted from the corresponding string pot measurements. Prior to each test, the string pots were zeroed as well as the LVDT and the geometry of the test setup was checked for accuracy.

3.5 Experimental Procedures for Notched Heavy Duty Pallets

3.5.1 Pallet Notching

Most of the wooden stringer pallets in circulation today are a partial four-way design. A two-way pallet is converted into a partial four-way pallet through a process known as notching. Pallet notches are created when two sections of wood are removed from a stringer to allow access for fork-truck tines. Notch locations are typically on the bottom of the stringers between the lead boards and the outer interior boards. Fork trucks are able to access partial four-way pallets from all four sides (Figure 14). However, a notched pallet has roughly 50% less strength than a non-notched pallet. Typically, notches are nine inches long, one and a half inches deep, and have half inch corner radii. For a typical 48inch by 40 inch pallet, the spacing between notches (inside corners) located on the same stringer is 18 inches and the notch location from the end of the stringer is six inches.

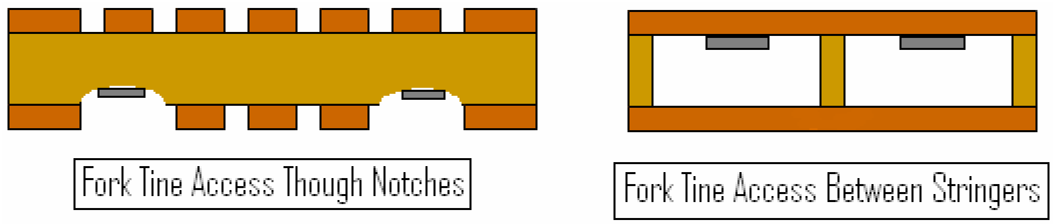

Figure 14: Fork truck access for partial four-way pallet.

In order to notch the pallet stringers, a notching jig was made by screwing together two pieces of 11/16 inch thick plywood (2¼in x 9in and 2in x 9in). The jig was designed to mark the outline of each notch with a pen by sliding it into each notch location. Once the outline was complete, a drill bit (0.10inch diameter) was used to mark the center of each corner through two holes. The notching jig is shown in Figure 15.

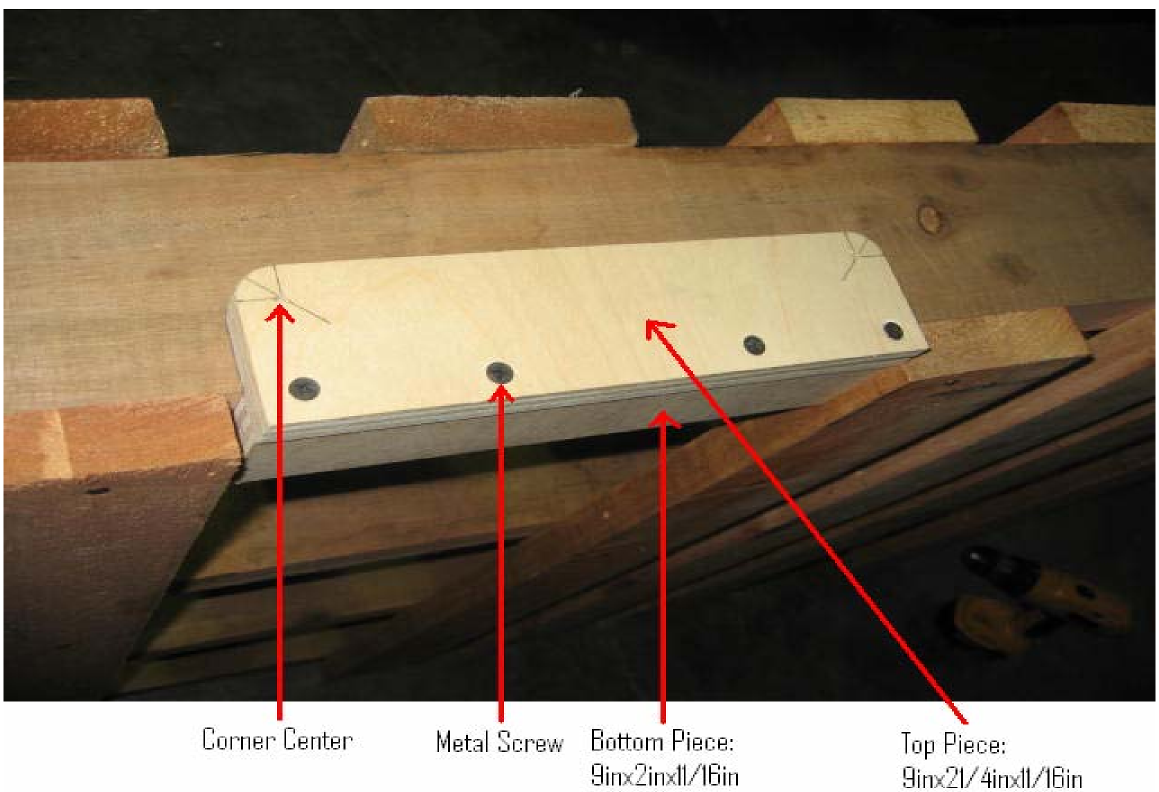

Figure 15: Photograph showing the notching Jig.

After each notch location was marked, the jig was removed and two holes (1 inch diameter) were drilled into both of the corners. Drilling one inch holes resulted in half inch corner radii for all notches. A 16 inch drill bit extension was added to access the center stringers. After all of the corner holes had been drilled, a hand saw was used to separate the vertical portions of the notch. A table saw was used to remove the remaining wood. In order to cut one and a half inch depths, multiple passes into each notch were made with the table saw. The remaining wood sections were then removed with a wood chisel and file. After the notching was complete, all nine pallets were retested to analyze the stiffness in racking conditions as well as other support conditions.

3.5.2 RAL Testing of Heavy Duty Partial 4-Way Pallets

As mentioned in section 3.4.3, the stringers are the critical pallet components in RAL testing. Notching a wooden stringer pallet reduces the maximum load the pallet can support. Because the nine pallets were previously tested without notches, it was necessary to determine new test loads. Test load levels were determined from the pallet design analysis outputs found in Appendix A, Figures 15, 16, and 17.

The notched RAL test setup was identical to the non-notched RAL test setup. Figure 18 in Appendix A shows the notched RAL test setup. Refer to section 3.4.3 for RAS test preparations. The test loads for notched RAL tests are given below in Table 5.

Table 5. Test loads for notched pallet bending tests.

Notched Thick Pallet Racking Loads (lbs)					
Pallet Design	RAL	RAW	Forktine	Top Floor	Bottom Floor
3-Stringer	2500	3500	7500	NA	NA
4-Stringer	3714	3800	9863	NA	NA
5-Stringer	4649	3991	11471	NA	NA

3.5.3 RAW Testing of Heavy Duty Partial 4-Way Pallets

When testing RAW, the stringers are not the critical members of the pallets. However, the span/s between the center stringer/s effect the stiffness of the top and bottom deck boards. For this reason, it was necessary to conduct RAW tests in order to understand how the notches affect the racking performance of the pallets.

The notched RAW test setup was identical to the non-notched RAW test setup. Figure 19 in Appendix A shows the notched RAW test setup. Refer to section 3.4.4 for RAD test preparations. The test loads for notched RAW tests are given in Table 5.

3.5.4 Fork Tine Support Testing of Heavy Duty Partial 4-Way Pallets

Fork tine support testing can be conducted in two ways on partial 4-way stringer pallets, perpendicular to the deck boards and perpendicular to the stringers. In section 3.4.5, fork tine support tests were conducted with the supports located perpendicular to and in between the lower and upper deck boards. This is because fork trucks can only access two-way pallets from the end parallel to the stringers. However, notches allow fork trucks to access partial four-way pallets through all ends and sides. The fork tine support tests for the notched pallets were in the notches perpendicular to the stringers. The support conditions for notched fork tine support tests were changed to analyze the pallets stiffness after being notched. The notched fork tine support test setup is shown below in Figure 16.

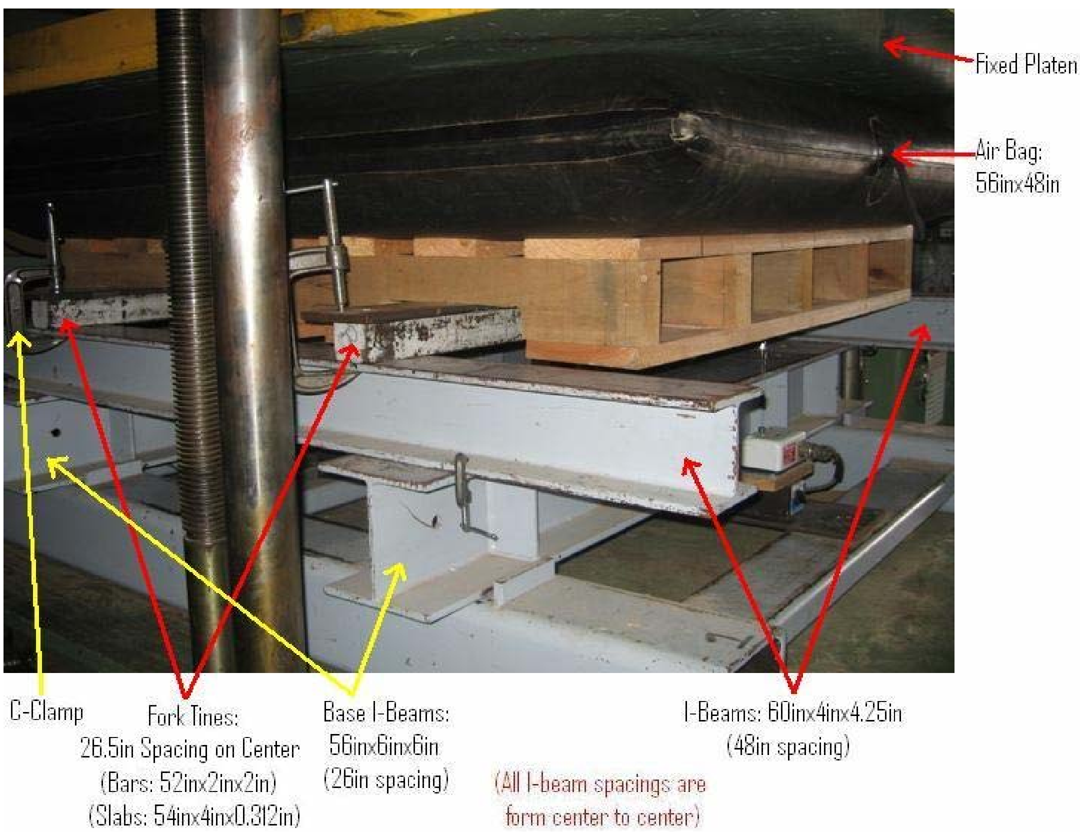

Figure 16: Photograph of fork tine support spanning the pallet width.

Similar to methods described in section 3.4.5, a prototype pallet was used to determine the notched fork tine support test loads. The prototype pallet was a four stringer partial four-way pallet. It was first tested RAL with the same test set-up that was used in sections 3.4.3 and 3.5.2. The notched fork tine test setup was assembled and the same scrap pallet used for the RAL test was retested. Corresponding load measurements from each test were recorded at 0.20 inch deflections. Data from these tests were combined with data from a notched four stringer RAL test to form a proportional relationship solving for an unknown.
An example calculation for notched fork tine test loads is given below.

$$\frac{NRAL}{NForkTine} = \frac{NRAL}{x} \quad : \quad \frac{1476lbs}{5975lbs} = \frac{2357lbs}{x} \quad : \quad \text{x = 9543 lbs} \qquad [5]$$

Where:

N RAL = Notched RAD test load (prototype pallet): 1476 lbs

N Fork Tine = Notched fork tine test load (prototype pallet): 5975 lbs

N RAL = Notched RAD test load (test pallet): 2357 lbs

x = Notched fork tine test load (test pallet): 9543 lbs

To prevent pallet damage, the test loads had to be adjusted during the first notched fork tine support test. The test profile was setup to apply 9543 pound loads to all three stringer pallets. However, adequate deflections of 0.25 inch were measured at 7500 pounds. The equation below demonstrates how the notched fork tine test loads were adjusted for all four and five stringer pallets.

$$\frac{3stringer(predicted)}{3stringer(actual)} = \frac{4or5stringer(predicted)}{4or5stringer(actual)} \qquad [6]$$

4 stringer : 9543 lbs/7500 lbs = 12550 lbs/x : x = 9863 lbs

5 stringer : 9543 lbs/7500 lbs = 14596 lbs/x : x = 11471 lbs

For each test, three string pots were attached to I-hooks screwed into the bottom surface of the pallet. The string pot locations can be found in Figure 10 of Appendix A. Do to a limited amount of space in the test set-up, the yoke could not be used to support the LVDT. Similar to section 3.4.5, a lab clamp stand was used to support the LVDT for all notched fork tine support tests. The stand held the LVDT, allowing it to measure the amount of deflection from the fork tine surface in reference to the base of the compression machine. A C-clamp was clamped to the fork tine directly between two stringers. Woven filament line was looped from the C-clamp in order to attach the LVDT core. The lab clamp stand and LVDT are shown in Figure 20 of Appendix A. Prior to each test, the string pots were zeroed as well as the LVDT and the geometry of the test setup was checked for accuracy.

3.6 Experimental Procedures for Light Duty Pallets

3.6.1 Pallet Component Manufacturing

Three pallets were assembled in order to gain a better understanding of pallet stiffness of pallets with thinner components. The pallets described in prior sections were extremely stiff and lacked flexibility even under high loads. It was apparent that pallets with more flexibility would deflect more under applied loads. Increased flexibility would assist in the understanding of how joint stiffness affects pallet deflection. Different joint (heavy duty and light duty) stiffness is discussed in Chapter 4.

New materials of the same species, grade, and moisture content were gathered to be manufactured into the thinner pallet component dimensions listed in section 3.3. A wood planer was used to remove one half inch of material from the thickness of all deck boards and lead boards and one quarter inch of material from the thickness of all stringers.

3.6.2 Pallet Component Testing (MOE)

The MOE for all new pallet components were measured. To verify FEA model predictions, the MOE for each component was needed to analyze the overall stiffness of the pallets. The same methods described in section 3.4.1 were used here. The single point bending test for a deck board is shown in Figure 1 of Appendix A. The average MOE for the thinner pallet components are given in Table 6.

Table 6: Average modulus of elasticity for light duty pallet components.

Component	MOE (psi)	COV (%)
Deck boards	2,200,000	14.2
Lead boards	2,200,000	12.1
Stringers	1,300,000	13.4

3.6.3 Pallet Assembly

The assembly process for the light weight pallets mimicked the assembly process for thick pallets. Both the pallet jig and nailing jigs were adjusted to compensate for the thinner 1½ inch stringers. Refer to section 3.4.2 for specific pallet assembly materials and procedures.

3.6.4 Test Procedure for RAW Pallet Bending Tests

The same methods in section 3.4.4 were used for the light duty pallet RAW bending test procedure. Light duty pallet test loads are shown below in Table 7.

Table 7: Test loads for light duty pallet bending tests.

Light Duty Pallet Racking Loads (lbs)					
Pallet Design	RAL	RAW	Forktine	Top Floor	Bottom Floor
3-Stringer	NA	1348	4000	5000	3126
4-Stringer	NA	1892	4308	12610	7882
5-Stringer	NA	2048	4983	21436	13397

3.6.5 Test Procedure for Fork Tine Pallet Bending Tests

The same methods in section 3.4.5 were used for the light duty pallet fork tine bending test procedure. Refer to Table 7 in section 3.6.4 for fork tine pallet bending test loads.

3.6.6 Test Procedure for Top Deck Floor Stack Pallet Tests

A wooden pallet supporting a unitized load on a solid, flat surface is considered to be floor stacked. Pallets are commonly floor stacked in staging areas of distribution centers (DCs). Unit loads (pallets containing products) can be floor stacked multiple units high, subjecting the upper and lower deck boards to bending stresses.

The test set up was changed to the floor stack support condition. Steel eye-beams (60in x 4in x 4.25in) were used to support each stringer, simulating a flat, rigid surface. The number of I-beams used in each test corresponded with the number of stringers in the test pallet. Each I-beam was secured to the base I-beams using two C-camps. The test set up for a top deck four stringer floor stack test is shown below in Figure 17.

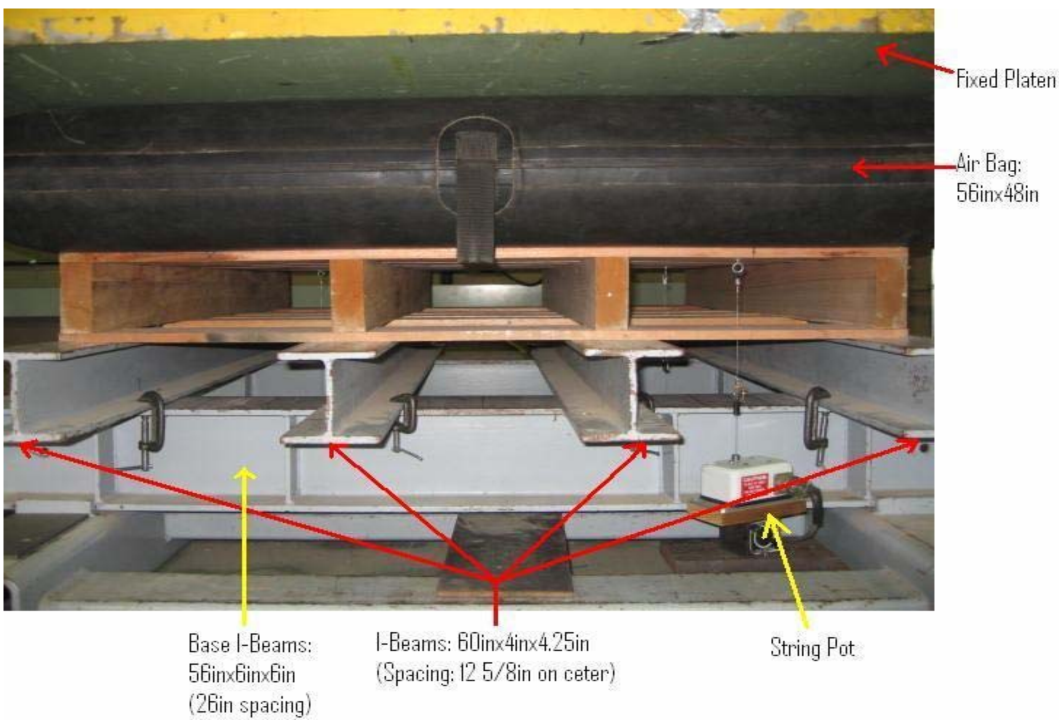

Figure 17: Test set up for light duty four stringer top deck floor stack.

Three string pots were used to measure top deck board deflections. Holes of three eighths inch diameter were drilled through the bottom deck boards in order to hang the string pots from the bottom surface of the top deck boards. For five stringer floor stack bending tests, the string pots were attached in the spans surrounding the center stringer. The string pot locations for top and bottom deck floor stack tests are shown in Figure 18.

String pot 3 was located on the center interior deck board, string pot 1 was located on the adjacent interior deck board, and string pot 5 was located on the end board.

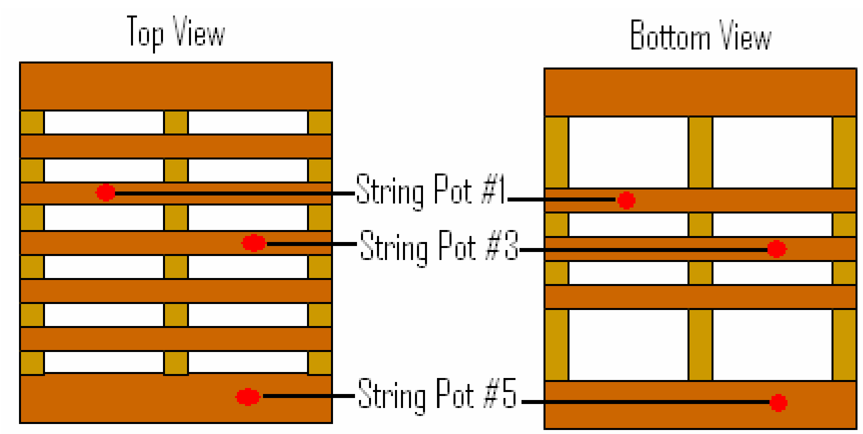

Figure 18: String Pot Locations for Top and Bottom Deck Floor Stack Tests.

A +/- one inch travel LVDT was used to measure the amount of deflection of steel in the test supports. To do this, a rectangular aluminum rod was c-clamped to the top surface of the outer most I-beam supporting the pallets. Woven filament line was looped around the end of the rod in a small groove and used to hang the LVDT rod. A lab clamp stand was used to hold the LVDT in place for each test. After each floor stack test was complete, the LVDT measurements were subtracted from the string pot measurements in order to determine the compliance of the test set up as well as the deck board deflections. The LVDT set up for floor stack tests can be seen below in Figure 19.

Figure 19: LVDT set up for light duty pallet floor stack tests.

The top deck floor stack test loads were determined from the computer generated outputs. Table 7 in section 3.6.4 show the top deck floor stack bending test loads. The test loads used for top deck tests were greater then the computer generated outputs (Figures 5-7 in Appendix A) in order to obtain 0.2 inch deck board deflections. Prior to each top deck test, the string pots were zeroed as well as the LVDT and the geometry of the test set up was checked for accuracy.

3.6.7 Pallet Test Procedure for Bottom Deck Floor Stack Pallet Bending Tests

Because pallets containing unitized loads are commonly floor stacked multiple units high, the bottom deck boards experience load stresses similar to the top deck boards. Various products transported on wooden pallets (pails, sacks, containers) have different effects on load distribution through the deck boards. The bottom surface of a non-reversible, two-way wooden pallet contains large spaces between the interior deck boards and the lead boards. Loads are distributed differently across the bottom deck boards as compared to the top surface of the same pallet, depending on the type of product. It was necessary to measure the difference in deflections between the top and bottom deck boards in floor stacking conditions to accurately calibrate the ANSYS model outputs.

Before the bottom deck board floor stack tests were conducted, a 1/8 inch rubber mat was placed over the bottom surface the three stringer pallet in between the air bag and the bottom deck boards. The mat was used to prevent the air bag from over penetrating the voids between the interior deck boards and the lead boards on the bottom surface of the pallet. After a trial test was conducted with a 3126 pound load, the mat was removed and the pallet was retested with the air bag in direct contact with the bottom surface. After both tests were complete, it was apparent that the rubber mat had no effect on the air bag penetration between the interior deck boards and the lead boards. All bottom deck floor stack bending test were conducted with the air bag directly on the bottom deck of each pallet.

Figure 21 in Appendix A shows the test set up for a three stringer bottom deck floor stack bending test. Holes of three eighths inch diameter were drilled through the top deck boards in order to attach the string pots from the bottom surface of the bottom deck boards. Refer to Figure 18 in section 3.6.6 for the string pot locations used in the bottom deck floor stack bending tests. Refer to Figure 19 in section 3.6.6 for the bottom deck floor stack LVDT set up. Refer to Table 8 in section 3.6.4 for the bottom deck floor stack test loads. Prior to each bottom deck floor stack bending test, the string pots were zeroed as well as the LVDT and the geometry of the test set up was checked for accuracy.

Chapter 4

Pallet Test Results

4.1 Results and Discussion

The main focus of this research was to produce wood pallet test data to validate FEA structural models.

After each pallet bending test was complete, a series of steps were taken in order to determine the linear portion of each load-deflection curve representing deflection measurements from three string pots and one LVDT. First, all three string pot deflection measurements were plotted against the LVDT deflection in order to look at the shape of the load vs. deflection relationship. Next, Pot 1 and the LVDT were plotted against the average test load throughout each test. String Pot 1 was used because it was measuring deflections in approximately the same location as the LVDT. The LVDT deflection measurements were also plotted in order to further understand the compliance of the test set up. A trend line was added to each of the two load-deflection curves to determine linearity as seen in Figure 20.

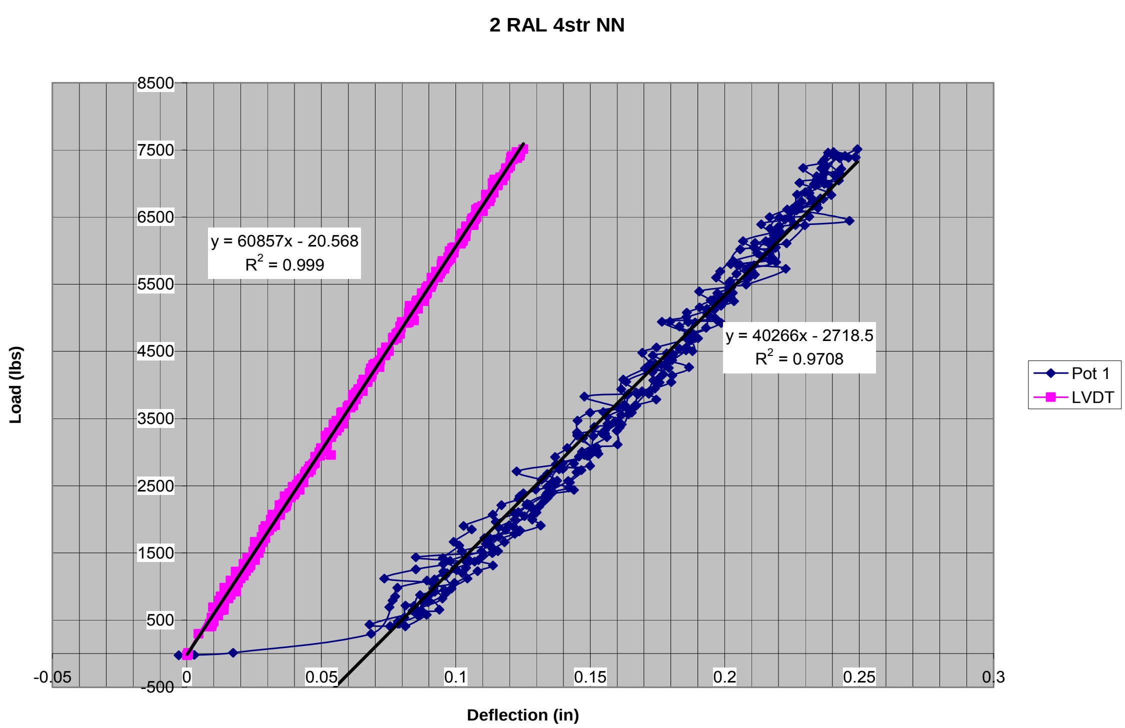

Figure 20: Graph showing the load-deflection curves for a heavy duty RAL test.

The trend line was used to remove measurements taken as the test specimen settled under applied loads. After the linear portion of each load-deflection curve was determined, a new graph was made showing the load-deflection curve for the linear portion of the third load cycle from each test. This was done to ensure the data represented the pallet stiffness after the joints were adequately flexed. Figure 21 shows the linear portions of string pot 1 and the LVDT deflections for heavy duty RAL test curves, representing only the third loading cycle.

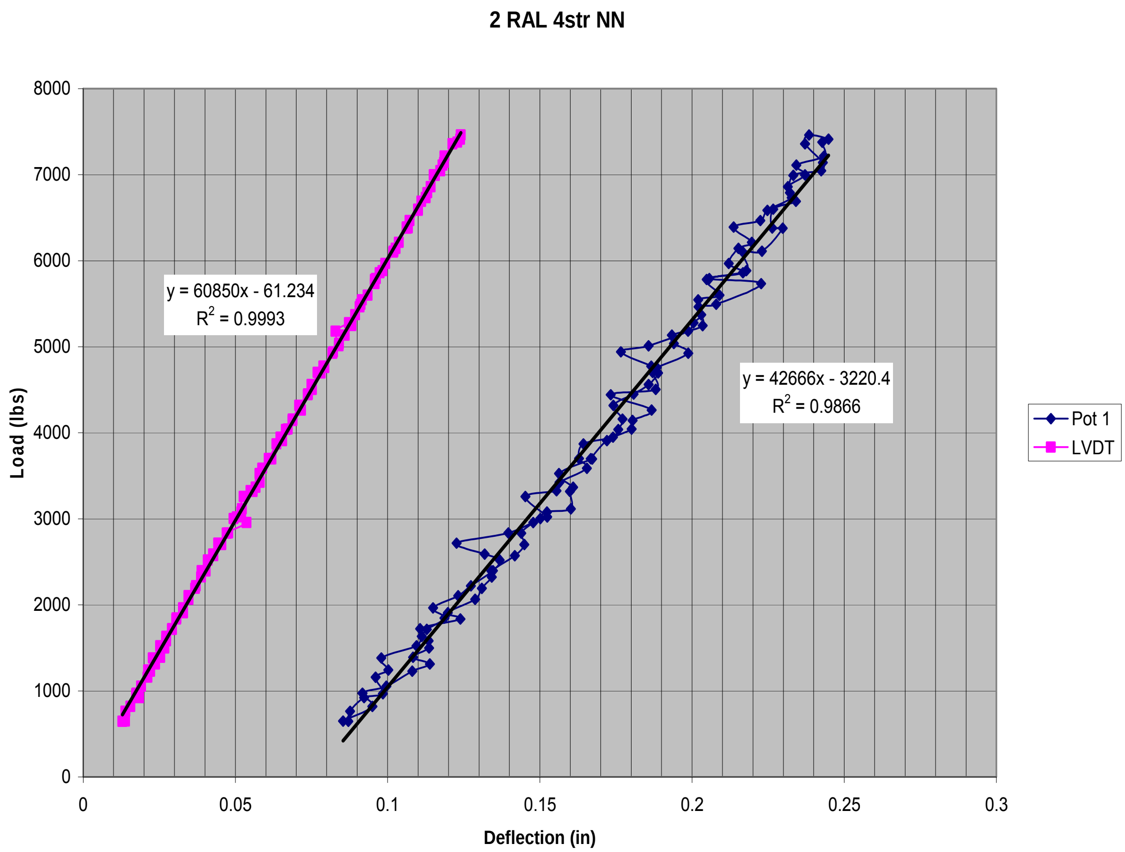

Figure 21: Graph showing adjusted pot 3 and LVDT curves (3rd load cycle) for a RAL test.

Both load and deflection measurements were extracted from string pot 1 curves along with the corresponding LVDT measurements. After this was complete for each pallet bending test, summary tables were created for heavy duty and light duty test results. The tables contained pallet deflections from the three string pot locations (adjusted for compliance) and the corresponding test loads. P_1 and Δ_1 measurements were extracted from the beginning of each linear curve and P_2 and Δ_2 measurements were extracted from the end of each linear curve. The stiffness of each pallet was determined by dividing the difference of P_1 and P_2 by the difference of Δ_1 and Δ_2.

The heavy and light duty pallet bending test results are located in Tables 2 and 3 of Appendix B respectively. Tables 2 and 3 of Appendix B are color coordinated to aid in telling the difference between 3, 4, and 5 stringer results.

4.2 Pallet Bending Test Results

The pallet bending test results show the effect of pallet design parameters on the stiffness of the wood pallets tested for this research. The effect of notching, component thickness, and the number of components on the stiffness of the pallets are discussed in this section. The pallet design directly affects the stiffness of the pallets tested with the different support conditions used throughout this research.

As stated in prior sections, twelve pallets were constructed for this research. Nine of the pallets were heavy duty (1.0 inch deck boards) and 3 were light duty (0.5 inch deck boards). It is hypothesized that thinner pallet components reduce the stiffness of the pallet. For example, when pallets are tested RAW in a racking system, the deck boards are the critical component. Therefore pallets with thinner deck boards will deflect more than thicker deck boards resulting in lower pallet stiffness. Figure 22 is a graph showing the effect of deck board thickness on pallet stiffness in RAW bending tests.

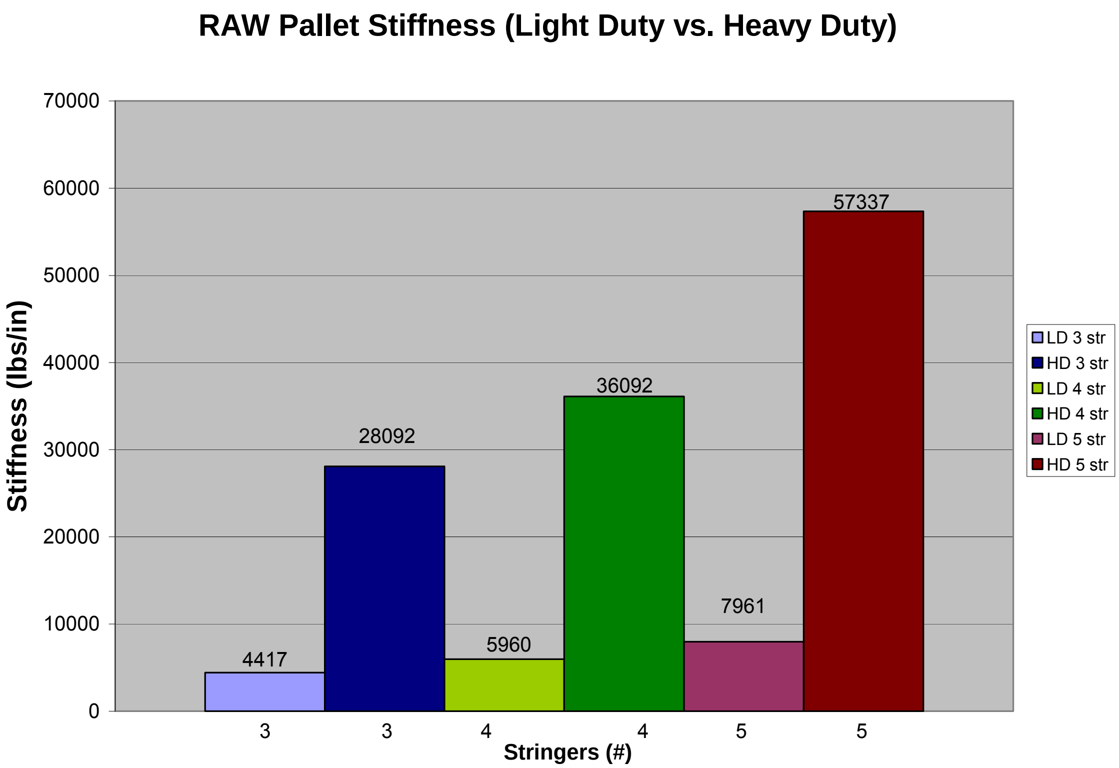

Figure 22: Graph showing the effect of deck board thickness on RAW pallet stiffness. (LD = Light Duty, HD = Heavy duty, str = stringers)

Figure 22 compares the stiffness of each of the light duty pallets tested RAW to the average stiffness of the 3, 4, and 5 stringer heavy duty pallets tested RAW. The heavy duty pallets are, on average, 6.5 times stiffer than the light duty pallets. This supports the hypothesis that thicker deck boards produce stiffer pallets. Pallet stiffness is influenced by component stiffness. Thicker components are stiffer than thinner components because of larger moment of inertia. Increased component thickness yields a higher moment of inertia thus increasing stiffness:

$$I = \frac{b * d^3}{12} \quad : \quad Stiffness = \frac{48EI}{l^3} \qquad [7]$$

Where:

I = Moment of Inertia (in^4)

b = Width (in)

d = Thickness (in)

E = MOE (PSI)

l = Length (in)

The effect of notching on the stiffness of a wood stringer pallet is substantial. Stringer stiffness can be reduced by approximately 50% after it is notched, depending on the size of the notch. Stringer stiffness decreases as the notch length and depth increase. However, the most critical portion of the notch is the corner fillet. When pallets are tested for strength, the typical failure location is corner fillet for RAL bending tests. The corner fillets were made with a radius to reduce the stress concentration found in a 90° corner fillet. Typical corner fillet radii used by the pallet industry are one inch, half inch, and quarter inch. A half inch radius corner fillet was used when notching the nine heavy duty pallets tested for this research. Figure 23 is a graph showing the effect of notching on pallet stiffness in RAL bending tests.

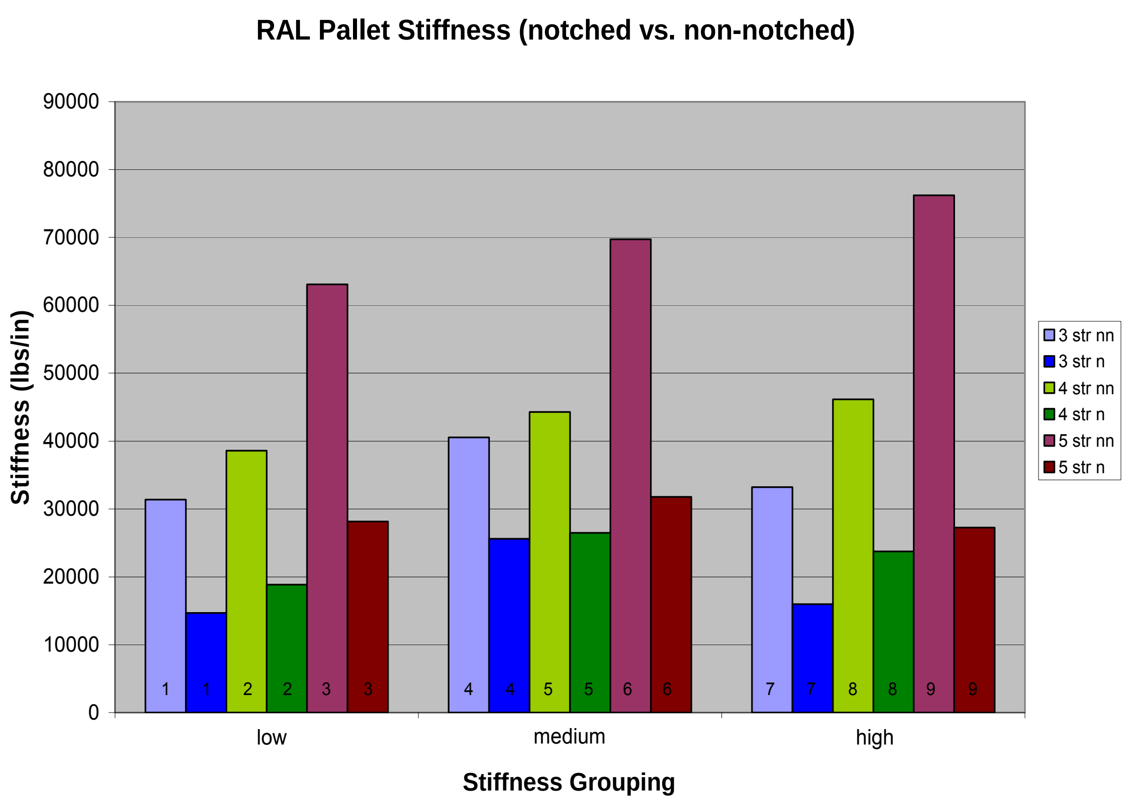

Figure 23: Graph showing the effect of notching on pallet (#1-9) stiffness in RAL bending tests. (LD = Light Duty, HD = Heavy duty, str = stringers)

Figure 23 contains the notched and non-notched pallet stiffness. The nine heavy duty pallets are separated into the three different stiffness groups; low, medium, and high. Before the pallets were assembled, the pallet components were grouped based on MOE. Therefore, in each of the three groups there is a 3, 4, and 5 stringer pallet. Two bars are shown for each pallet representing non-notched and notched bending test results. Based on the results shown in Figure 16, the overall average stiffness for all heavy duty RAL pallet bending tests was reduced by 51% after notching. This supports the hypothesis that notched pallets are less stiff than non-notched pallets.

A notched pallet contains less stringer material than a non-notched pallet, causing a transformation in the effective depth of the stringers. Therefore, non-notched stringers have greater moments of inertia making them stiffer than notched stringers. Refer to Equation 4 for further explanation.

Another difference in pallets which is known to affect stiffness is the overall design of the pallet. The addition or removal of stringers and deck boards change the pallet design and directly influence the stiffness of the pallet. Figure 24 shows a comparison of the stiffness of heavy duty and light duty non-notched fork tine support bending tests. The heavy duty pallet results are based on the average stiffness of the 3, 4, and 5 stringer pallets.

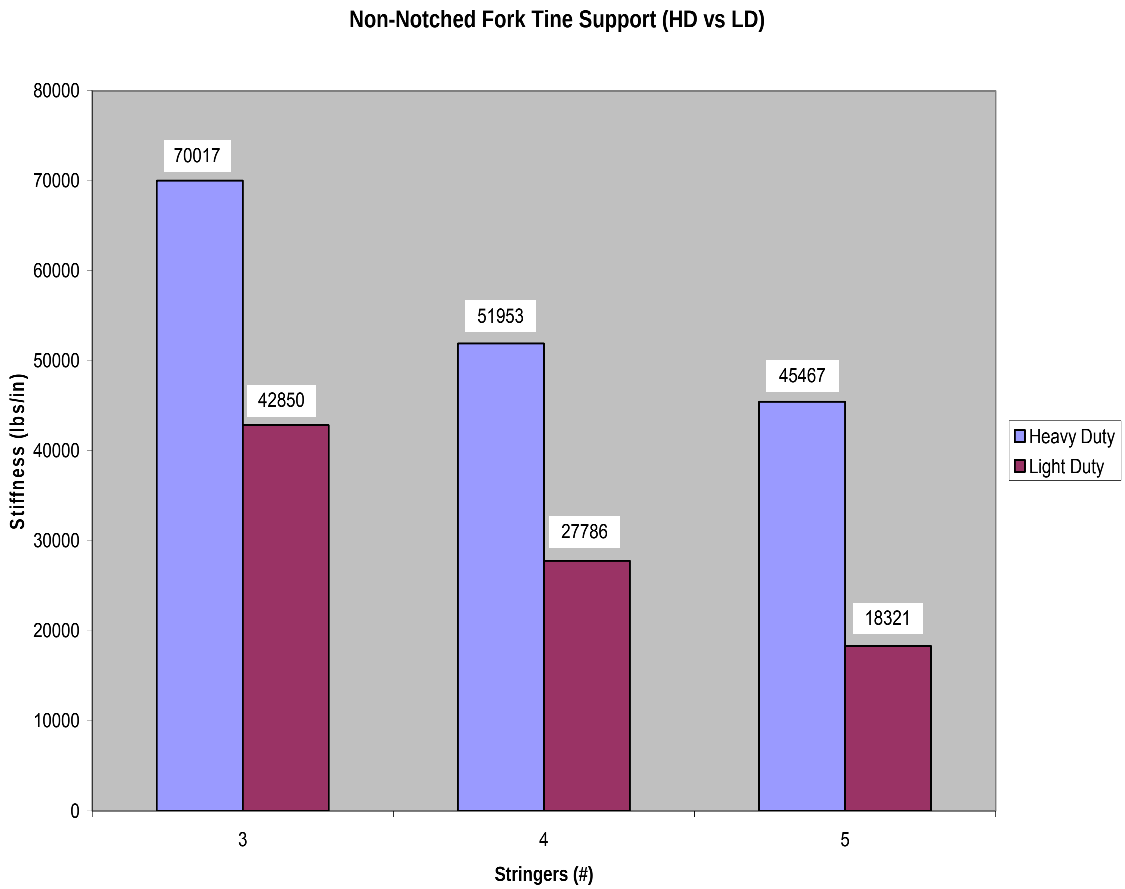

Figure 24: Graph showing the effect of pallet design on stiffness for non-notched fork tine support testing.

Figure 24 shows that the light duty pallets are less stiff than the heavy duty pallets in non-notched fork tine support conditions. The graph also shows decreased pallet stiffness as the support conditions were changed for the different pallet designs. Three stringer pallets were stiffer that five stringer pallets because the support span was 9 ⅛ inches longer for five stringer fork tine support tests than for 3 stringer pallets. More specifically, the average stiffness of 3, 4, and 5 stringer light duty pallets were 39%, 46%, and 60% less stiff respectively, when tested with the fork tine support between the deck boards.

The bending theory, shown in Equation 5, can be used to explain the stiffness reduction in fork tine support bending tests. Pallet stiffness decreased (on average) by 29% and 20% as the fork tine support span (l) increased for 4 and 5 stringer pallet bending tests:

$$\frac{P}{\Delta} = \frac{KEI}{l^3} \qquad [8]$$

Where:

P = Load (lbs.)

Δ = Deflection (in.)

K = Constant

E = MOE

I = Moment of inertia ($in.^4$)

l = length between supports (in.)

4.3 Pallet Bending Test Summary Tables

Pallet bending test results were compiled into four summary tables (Tables 8 through 11), each containing results for the different support conditions. Heavy/light duty and notched/non-notched results are included in the summary tables. The average MOE for pallet components and average rotation modulus and withdrawal stiffness for each pallet style are shown in the summary tables. Adjusted string pot deflections and corresponding uniform loads are shown in the summary tables.

Data from the summary tables (Tables 8 through 11) was compared with structural analysis models developed with ANSYS (Version 11). Following the summary tables are graphs showing experimental results compared with outputs from a select number of structural analyses.

Table 8: RAL pallet bending test summary table.

Non-Notched RAL Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str NN)	1672921	1507175	1352523	6758	57823	2014	0.04	0.06	0.01	4083	0.09	0.12	0.06	31391
#2 (4 str NN)	1855000	1586184	1455816	6758	57823	4038	0.07	0.06	0.01	6142	0.10	0.11	0.06	38581
#3 (5 str NN)	1944640	1644700	1514546	6758	57823	4012	0.06	0.08	0.01	7975	0.11	0.14	0.06	63091
#4 (3 str NN)	2069102	1700705	1559262	6758	57823	2033	0.05	0.09	0.07	4062	0.09	0.14	0.11	40542
#5 (4 str NN)	2178449	1783731	1628944	6758	57823	3000	0.04	0.06	0.02	5995	0.08	0.13	0.07	44304
#6 (5 str NN)	2292622	1892734	1683425	6758	57823	3999	0.06	0.08	0.03	8105	0.11	0.13	0.08	69720
#7 (3 str NN)	2394770	1975624	1706060	6758	57823	2039	0.04	0.05	0.04	4092	0.08	0.11	0.07	33211
#8 (4 str NN)	2540374	2079662	1761287	6758	57823	3103	0.04	0.02	0.00	5427	0.08	0.07	0.04	46168
#9 (5 str NN)	2743057	2204934	1947873	6758	57823	4010	0.04	0.04	0.02	8059	0.09	0.09	0.06	76223
Notched RAL Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str N)	1672921	1507175	1352523	6758	57823	1519	0.08	0.12	0.12	2016	0.10	0.15	0.15	14691
#2 (4 str N)	1855000	1586184	1455816	6758	57823	2005	0.08	0.10	0.10	2774	0.11	0.14	0.13	18857
#3 (5 str N)	1944640	1644700	1514546	6758	57823	2099	0.08	0.09	0.05	4061	0.14	0.16	0.11	28143
#4 (3 str N)	2069102	1700705	1559262	6758	57823	1504	0.07	0.11	0.10	2063	0.10	0.13	0.13	25627
#5 (4 str N)	2178449	1783731	1628944	6758	57823	2020	0.08	0.11	0.11	3178	0.11	0.15	0.14	26478
#6 (5 str N)	2292622	1892734	1683425	6758	57823	2007	0.07	0.08	0.07	4044	0.13	0.14	0.13	31785
#7 (3 str N)	2394770	1975624	1706060	6758	57823	1643	0.08	0.08	0.09	1946	0.09	0.10	0.11	15980
#8 (4 str N)	2540374	2079662	1761287	6758	57823	2011	0.06	0.07	0.08	3041	0.09	0.11	0.11	23772
#9 (5 str N)	2743057	2204934	1947873	6758	57823	2037	0.05	0.05	0.07	4079	0.10	0.13	0.13	27269

(* = Deflection)

Table 9: RAW pallet bending test summary table.

Non-Notched RAW Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str NN)	1672921	1507175	1352523	6758	57823	2052	0.09	0.07	0.10	4007	0.16	0.14	0.15	31485
#2 (4 str NN)	1855000	1586184	1455816	6758	57823	2999	0.10	0.08	0.06	5061	0.16	0.13	0.09	44250
#3 (5 str NN)	1944640	1644700	1514546	6758	57823	3099	0.10	0.09	0.08	4421	0.14	0.13	0.12	32282
#4 (3 str NN)	2069102	1700705	1559262	6758	57823	2580	0.10	0.08	0.07	3959	0.15	0.13	0.10	29057
#5 (4 str NN)	2178449	1783731	1628944	6758	57823	3001	0.11	0.11	0.11	5090	0.17	0.18	0.20	27861
#6 (5 str NN)	2292622	1892734	1683425	6758	57823	3049	0.10	0.09	0.10	4514	0.14	0.15	0.15	24351
#7 (3 str NN)	2394770	1975624	1706060	6758	57823	2077	0.06	0.10	0.16	3543	0.11	0.16	0.22	23734
#8 (4 str NN)	2540374	2079662	1761287	6758	57823	2961	0.08	0.07	0.07	5042	0.13	0.13	0.12	36166
#9 (5 str NN)	2743057	2204934	1947873	6758	57823	3092	0.06	0.06	0.06	4982	0.10	0.07	0.06	115378
Light Duty														
#1 (3 str NN)	1871344	1975167	1161295	12907	44008	663	0.22	0.22	0.25	1348	0.35	0.38	0.41	4417
#2 (4 str NN)	2198136	2152044	1310276	12907	44008	633	0.20	0.21	0.22	1497	0.35	0.36	0.36	5960
#3 (5 str NN)	2563822	2518765	1530537	12907	44008	820	0.18	0.17	0.14	1536	0.26	0.26	0.25	7961
Notched RAW Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str N)	1672921	1507175	1352523	6758	57823	2609	0.10	0.06	0.05	3290	0.13	0.09	0.08	21009
#2 (4 str N)	1855000	1586184	1455816	6758	57823	2519	0.07	0.03	0.02	3225	0.09	0.06	0.04	29143
#3 (5 str N)	1944640	1644700	1514546	6758	57823	2755	0.08	0.12	0.18	3886	0.12	0.16	0.23	25258
#4 (3 str N)	2069102	1700705	1559262	6758	57823	2528	0.09	0.07	0.06	3437	0.12	0.10	0.09	30889
#5 (4 str N)	2178449	1783731	1628944	6758	57823	1518	0.06	0.06	0.09	3085	0.11	0.12	0.17	26397
#6 (5 str N)	2292622	1892734	1683425	6758	57823	1989	0.08	0.08	0.10	3002	0.11	0.13	0.15	20904
#7 (3 str N)	2394770	1975624	1706060	6758	57823	2500	0.07	0.10	0.18	3553	0.11	0.13	0.20	41343
#8 (4 str N)	2540374	2079662	1761287	6758	57823	2753	0.08	0.06	0.08	3612	0.10	0.08	0.10	37657
#9 (5 str N)	2743057	2204934	1947873	6758	57823	2546	0.05	0.02	0.01	3514	0.07	0.03	0.02	173306

(* = Deflection)

Table 10: Fork tine support pallet bending test summary table.

Non-Notched Fork Tine Support Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str NN)	1672921	1507175	1352523	6758	57823	6014	0.14	0.12	0.16	8105	0.17	0.15	0.20	74780
#2 (4 str NN)	1855000	1586184	1455816	6758	57823	4039	0.06	0.11	0.09	8026	0.12	0.18	0.15	55076
#3 (5 str NN)	1944640	1644700	1514546	6758	57823	4034	0.08	0.13	0.06	8019	0.13	0.24	0.11	38426
#4 (3 str NN)	2069102	1700705	1559262	6758	57823	4093	0.10	0.09	0.11	8034	0.17	0.14	0.18	73973
#5 (4 str NN)	2178449	1783731	1628944	6758	57823	4073	0.07	0.10	0.08	8002	0.11	0.18	0.12	50809
#6 (5 str NN)	2292622	1892734	1683425	6758	57823	4032	0.05	0.12	0.04	8009	0.10	0.20	0.09	48918
#7 (3 str NN)	2394770	1975624	1706060	6758	57823	4071	0.11	0.12	0.13	8009	0.18	0.18	0.22	61297
#8 (4 str NN)	2540374	2079662	1761287	6758	57823	4077	0.07	0.12	0.09	8116	0.12	0.20	0.14	49974
#9 (5 str NN)	2743057	2204934	1947873	6758	57823	4052	0.07	0.10	0.05	7021	0.09	0.16	0.09	49058
Light Duty														
#1 (3 str NN)	1871344	1975167	1161295	12907	44008	1193	0.10	0.05	0.06	3554	0.20	0.10	0.14	42850
#2 (4 str NN)	2198136	2152044	1310276	12907	44008	1434	0.03	0.09	0.07	3886	0.08	0.17	0.10	27786
#3 (5 str NN)	2563822	2518765	1530537	12907	44008	1629	0.03	0.14	0.05	4349	0.07	0.29	0.09	18321
Notched Fork Tine Support Bending Tests														
Heavy Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
#1 (3 str N)	1672921	1507175	1352523	6758	57823	3809	0.07	0.05	0.06	6120	0.09	0.07	0.08	124590
#2 (4 str N)	1855000	1586184	1455816	6758	57823	6229	0.09	0.12	0.18	9148	0.12	0.15	0.21	112152
#3 (5 str N)	1944640	1644700	1514546	6758	57823	7225	0.07	0.07	0.11	9973	0.08	0.09	0.13	144942
#4 (3 str N)	2069102	1700705	1559262	6758	57823	4321	0.11	0.10	0.09	6103	0.13	0.12	0.11	136320
#5 (4 str N)	2178449	1783731	1628944	6758	57823	5805	0.17	0.13	0.08	7873	0.19	0.15	0.10	127485
#6 (5 str N)	2292622	1892734	1683425	6758	57823	5319	0.06	0.06	0.07	9351	0.08	0.08	0.10	173944
#7 (3 str N)	2394770	1975624	1706060	6758	57823	3823	0.09	0.15	0.22	5897	0.11	0.17	0.24	241819
#8 (4 str N)	2540374	2079662	1761287	6758	57823	5642	0.12	0.13	0.15	8066	0.15	0.15	0.17	117911
#9 (5 str N)	2743057	2204934	1947873	6758	57823	5769	0.08	0.06	0.07	8553	0.09	0.08	0.08	169224

(* = Deflection)

Table 11: Floor stack support pallet test summary table.

Top Deck Floor Stack Tests														
Light Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
3 str NN	1871344	1975167	1161295	12907	44008	2453	0.09	0.05	0.04	4558	0.14	0.09	0.08	42452
4 str NN	2198136	2152044	1310276	12907	44008	7120	0.07	0.10	0.04	11926	0.10	0.13	0.06	153852
5 str NN	2563822	2518765	1530537	12907	44008	8184	0.08	0.10	0.05	16369	0.10	0.12	0.07	390192
Bottom Deck Floor Stack Tests														
Light Duty	Avg Deck Board MOE	Avg End Board MOE	Avg Stringer MOE	Avg Rot Mod (in-lbs/rad)	Avg Kwd (lbs/in)	Load 1 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Load 2 (lbs)	Pot 1* (in)	Pot 3* (in)	Pot 5* (in)	Stiffness (lbs/in)
3 str NN	1871344	1975167	1161295	12907	44008	1619	0.08	0.04	0.04	2850	0.13	0.07	0.06	43140
4 str NN	2198136	2152044	1310276	12907	44008	2573	0.02	0.01	0.01	6215	0.05	0.04	0.03	117879
5 str NN	2563822	2518765	1530537	12907	44008	6073	0.03	0.06	0.04	11053	0.04	0.08	0.05	231523

(* = Deflection)

4.4 Measured Results vs. Predicted Results

Using results from the summary tables, a select number of structural analyses were conducted using ANSYS (Version 11). The analyses used the same material properties (MOE) as the test pallets. The same load applied to each test pallet was used to generate predicted deflections supported RAL or RAW. Joint withdrawal stiffness from test results and linear tension spring constants from predicted results are also shown in Tables 12 through14. Although multiple structural analyses were conducted for each test with adjusted spring constants, only the deflections of closest similarity to measured deflections were used for comparison.

The difference between the measured and predicted results is due to test set up and comparison-based adjustment. The linear springs used for predicted results were adjusted to produce deflections similar to the measured results. The difference between K2 and Kwd can be explained using joint test methodology. The linear springs used to model pallet joints for predicted bending test deflections were a combination of linear springs in tension and compression. The springs in compression (K1) represent contact between the stringer edge and the deck board and the spring in tension (K2) represent the nail stiffness. The joint withdrawal stiffness (Kwd) represents the nail shank being withdrawn from the stringer. The measured connection stiffness did not reflect the stiffness parameter modeled.

The structural analysis deflections were recorded in the same locations as the string pots used for the actual pallet bending tests. The uniform loads shown in Tables 12 though 14 are the test loads from the end of the linear portion of each load/deflection curve.

Table 12: Measured and predicted deflections for heavy duty, 3 stringer, RAL bending tests.

Heavy Duty, 3 Stringer, RAL							
	Pallet #	Kwd (lbs/in)	P2	pot1 (in)	pot3 (in)	pot5 (in)	Avg Δ (in)
Tested	1	57823	4083	0.090	0.123994	0.062	
Predicted	1	1000	4083	0.061	0.116	0.061	
Predicted Δ Error (%)				-32%	-6%	-1%	-13%
Tested	4	57823	4062	0.089	0.141	0.105	
Predicted	4	1000	4062	0.075	0.126	0.075	
Predicted Δ Error (%)				-16%	-11%	-29%	-19%
Tested	7	57823	4092	0.080	0.108	0.074	
Predicted	7	1000	4092	0.071	0.115	0.071	
Predicted Δ Error (%)				-11%	7%	-5%	-3%

Table 13: Measured and predicted deflections for heavy duty, 3 stringer, RAW bending tests.

Heavy Duty, 3 Stringer, RAW							
	Pallet #	Kwd (lbs/in)	P2	pot1 (in)	pot3 (in)	pot5 (in)	Avg Δ (in)
Tested	1	57823	4007	0.156	0.136	0.155	
Predicted	1	1000	4007	0.148	0.143	0.148	
Predicted Δ Error (%)				-5%	5%	-4%	-2%
Tested	4	57823	3959	0.151	0.130	0.101	
Predicted	4	1000	3959	0.142	0.135	0.142	
Predicted Δ Error (%)				-6%	4%	42%	13%
Tested	7	57823	3543	0.111	0.160	0.216	
Predicted	7	1000	3543	0.108	0.102	0.108	
Predicted Δ Error (%)				-3%	-36%	-50%	-30%

Table 14: Measured and predicted deflections for light duty, 3, 4, and 5 stringer, RAW bending tests.

Light Duty, 3, 4, and 5 Stringer, RAW							
	Pallet #	Kwd (lbs/in)	P2	pot1 (in)	pot3 (in)	pot5 (in)	Avg Δ (in)
Tested	1	44008	1348	0.352	0.379	0.411	
Predicted	1	1000	1348	0.400	0.401	0.400	
Predicted Δ Error (%)				14%	6%	-3%	6%
Tested	2	44008	1497	0.348	0.356	0.358	
Predicted	2	1000	1497	0.364	0.361	0.364	
Predicted Δ Error (%)				5%	1%	2%	3%
Tested	3	44008	1536	0.261	0.255	0.252	
Predicted	3	5000	1536	0.260	0.258	0.260	
Predicted Δ Error (%)				-1%	1%	3%	1%

Figures 25 through 28 compare measured and predicted deflections from Tables 12 through 14.

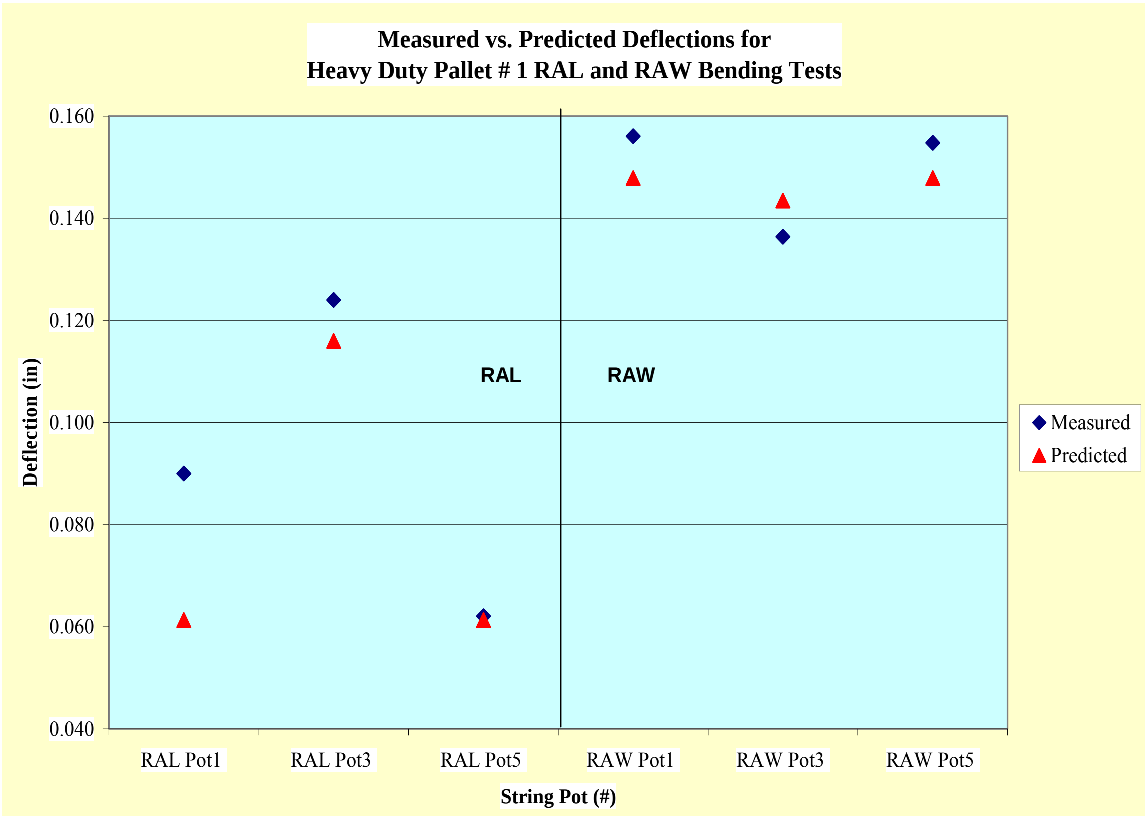

Figure 25: Graph comparing measured and predicted deflections for heavy duty pallet #1 RAL and RAW bending tests. (*adjusted x-axis*)

Figure 25 shows the measured and predicted deflections for heavy duty, Pallet number 1, RAL and RAW bending tests. The average predicted error for all heavy duty, pallet number 1, RAL and RAW bending tests were -13% and -2% respectively. The RAL predicted error was greater because string pot number 1 had a -32% error. This could have been due to experimental error caused by applying a non-uniform load to pallet number one during RAL support testing. Load bridging may have resulted from semi-rigid air bag properties. Another reason for the discrepancy could have resulted from the component stiffness (MOE) gradient used to assemble the pallets. String pot number 5 measured deflections from a stiffer stringer than string pot number 1. The structural analysis used component stiffness averages resulting more uniform deflection measurements.

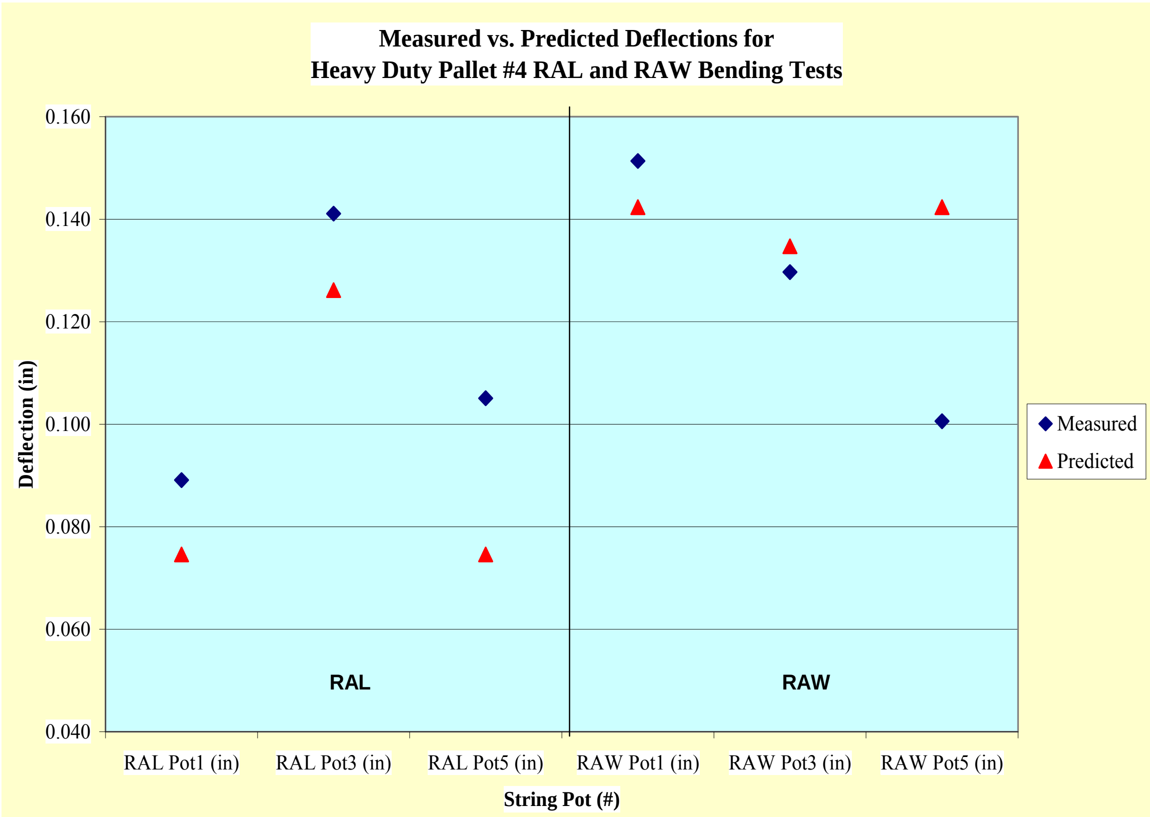

Figure 26: Graph comparing measured and predicted deflections for heavy duty pallet #4 RAL and RAW bending tests. (*adjusted x-axis).

Figure 26 shows the measured and predicted deflections for heavy duty, pallet number 4, RAL and RAW bending tests. The average predicted error for all heavy duty, pallet number 4, RAL and RAW bending tests were -19% and 13% respectively. RAW bending tests had a positive average predicted error because string pot 5 measured 42% greater deflections than predicted. String pot number 5 measured -29% and 42% predicted errors for pallet number 4 RAL and RAW bending tests respectively. Both of these errors could have resulted from non-uniform loading and component stiffness (MOE) assembly gradients. Typically, the string pot located in the center of the pallet measures the greatest deflections. However, string pot 1 measured higher deflections than string pot 3 for heavy duty (pallet number 4) RAW bending tests. The predicted results indicated that string pot 3 would have the lowest deflections in RAW bending tests.

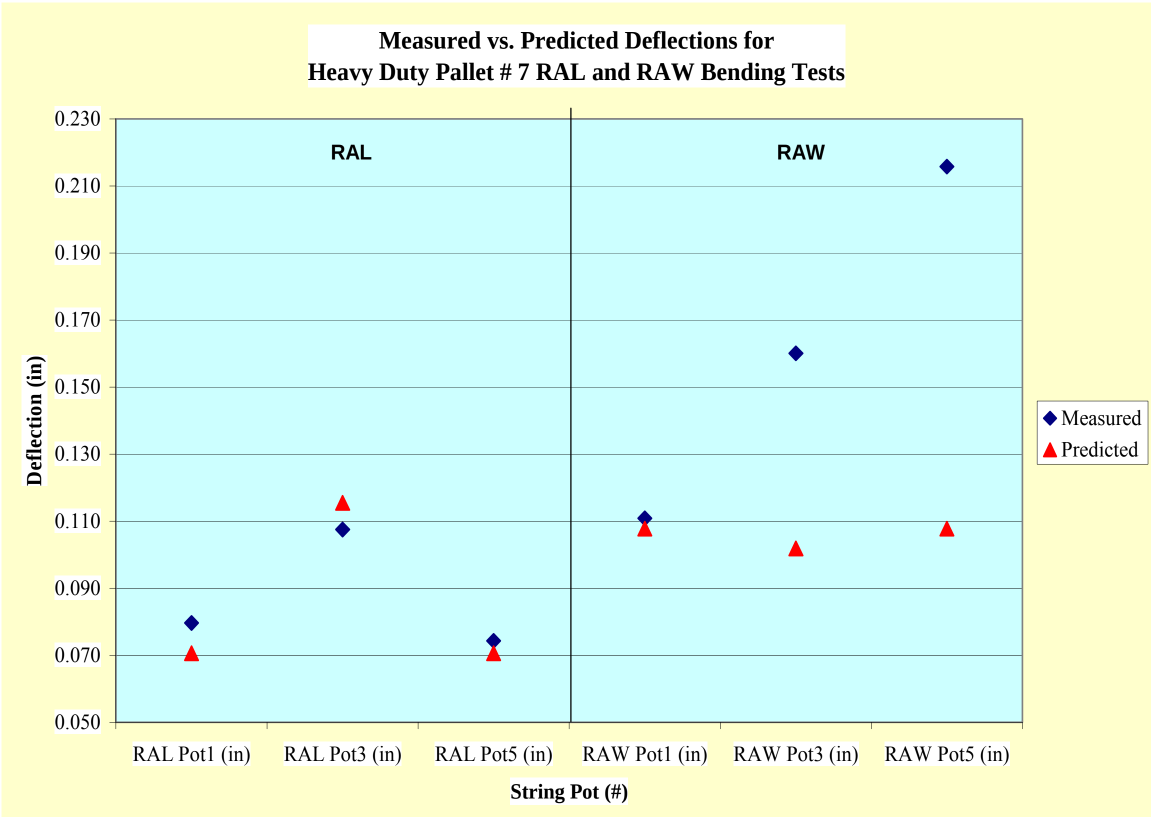

Figure 27: Graph comparing measured and predicted deflections for heavy duty pallet #7 RAL and RAW bending tests. (*adjusted x-axis*)

Figure 27 shows the measured and predicted deflections for heavy duty, pallet number 7, RAL and RAW bending tests. The average predicted error for all heavy duty, pallet number 7, RAL and RAW bending tests were -3% and -30% respectively. String pot number 3 and 5 had predicted errors of -36% and -50%. Measured RAW test results could have resulted from non-uniform loading or component stiffness assembly gradients.

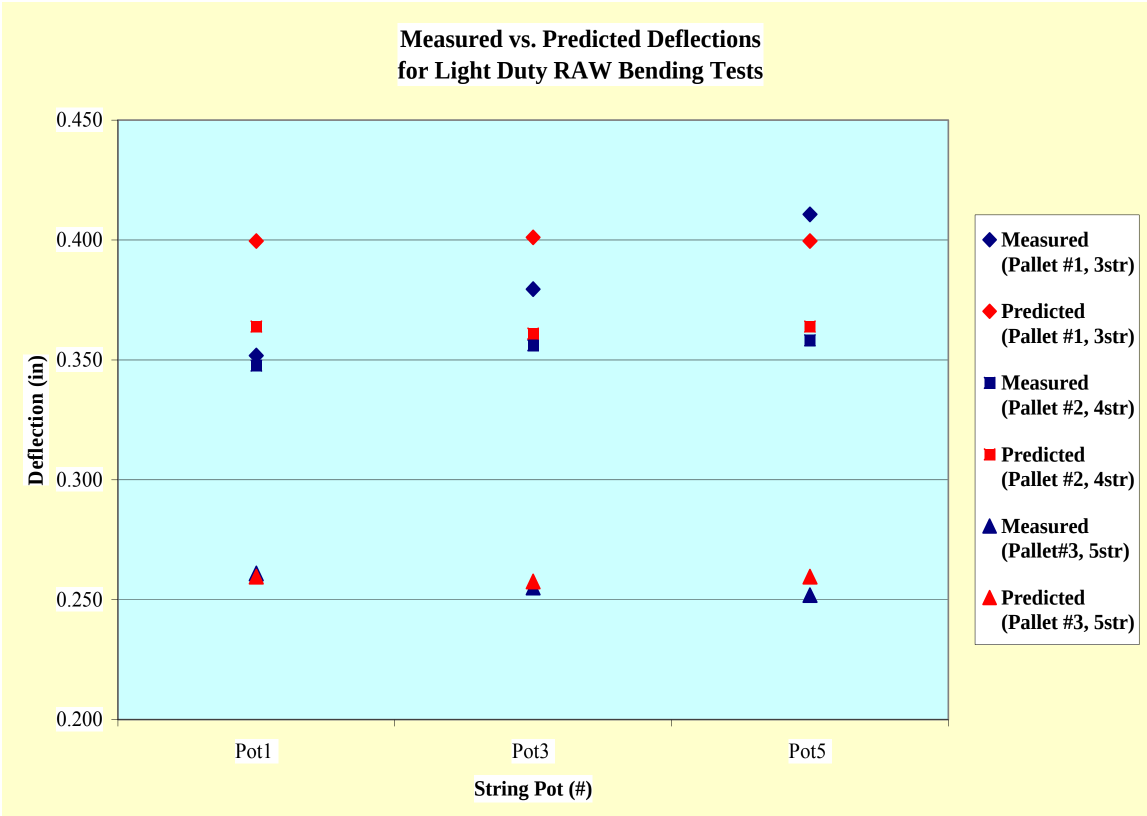

Figure 28: Graph Comparing measured and predicted deflections for light duty RAW bending tests. (*adjusted x-axis*)

Figure 28 shows the measured and predicted deflections for light duty, pallet number 1 (3 stringer), 2 (4 stringer), and 3 (5 stringer), RAW bending tests. The average predicted errors for pallets number 1, 2, and 3 were 6%, 3%, and 1% respectively. Overall, the deflection measurements for light duty RAW bending tests were similar for measured and predicted results.

4.5 Summary of Chapter 4

The previous chapter included the results from testing twelve wood pallets. Heavy and light duty pallets were assembled using 3, 4, and 5 stringer designs using clear, kiln dried Eucalyptus. The pallets were tested using RAL, RAW, fork tine, and top and bottom floor stack support conditions. Deflection measurements were recorded after various uniform loads were applied. Pallet stiffness was also determined for the different designs and support conditions.

Results indicate that pallets with thicker deck boards are stiffer in the RAW support condition. In the RAL support condition, results indicated an average decrease in stiffness of 50% for notched pallets, when compared to non-notched RAL bending test results. In both cases, the reduced moment of inertia proved to be the reason for loss of pallet stiffness. Results showed that pallet stiffness was reduced in fork tine support bending tests as the support span was increased. Reductions in pallet stiffness for fork tine support test were justified by the bending theory.

This research was unique because notch fork tine support tests have not been reported in literature. Currently, the only existing research investigating the effects of notching analyzed the strength of individual stringers. Rather than testing whole pallet specimens, Zalph (1989) studied how notching affects the strength of wood pallet stringers. Zalph (1989) used a simply supported bending test notched stringers on the ends Refer to chapter 2 for specific descriptions regarding notched pallet component performance.

The measured tests results from this research were compared with predicted results from ANSYS (version 11) structural analyses. Due to time and material limitations, only a select number of structural analyses could be completed. Predicted error was determined showing the difference between measured and predicted pallet bending test results.

Chapter 5

Literature Review: Nail Joint Testing

5.1 Introduction (Nail Joint Properties)

The common nailed wood joint has been used to join wood components together for centuries. This method of joining provided an economical yet safe way to join wood components in various wood structures, ranging from house construction to pallet manufacture (Samarasinghe, 1987).

The focus of most existing research on nailed wood joints is either determining maximum load capacity or predicting non-rigid stiffness. When determining the maximum load capacity, an assembled joint is tested to failure mimicking various loading conditions. Wallin and Stern (1974a) calculated the allowable lateral and static withdrawal loads by developing empirically based equations. They investigated both stiff-stock and hardened steel nails in the side grain of various lumber components.

Prior to the 1970's, many researchers modeled nail joints with the assumption that the connection was either rigid or pinned. A rigid connection has no mobility between members and a pinned connection has full mobility between members. However, in the early 1970's, researchers (Hoyle, 1970, Rassam and Goodman, 1970, Goodman et al., 1974, and Tremblay, 1974) determined that rigid and pinned joint models were inaccurate. Instead, spring elements of certain stiffness could be used by testing actual joints (Loferski, 1985). Loferski (1985) used zero length spring elements to model joint characteristics of stringer pallets and Colcolough (1987) used the same methodology to model block pallet joint characteristics.

In 1979, Kyokong stated that the rotation modulus and separation modulus are constants describing the degree of fixity of a nailed joint under a moment and axial force respectively. Further more, the separation modulus is defined as the ratio of applied withdrawal force to the corresponding separation and the rotation modulus is defined as the ratio of the applied moment to the angular rotation (Kyokong, 1979).

5.2 Key Influencing Variables on Nailed Wood Joint Performance

Samasinghe (1987) discussed the many variables that influence nailed wood joint performance. One of the variables which have the greatest effect on the stiffness of nailed wood joints is specific gravity (SG). Samarasinghe (1987) mentioned many investigators that found a direct relationship between SG of the wood members and the stiffness of a nailed joint. Scholten (1965) determined that the SG/maximum lateral load relationship is somewhat curvilinear. Samarasinghe (1987) mentioned Kuenzi (1955) and Wilkinson (1983) for their research indicating that the relationship between load and deformation is a function of the elastic bearing constant which is linearly related to SG. Linear relationships between SG and species constant factors, which are used as multipliers in describing load-slip behavior of short term loaded joints, were examined by Mack (1966). All of these investigations have led to the understanding that SG effects joint stiffness and performance.

Another key factor in nailed wood joint stiffness are the characteristics of the fastener. Samarasinghe (1987) mentioned the findings of two studies, Wallin and Stern (1974a) and Wallin (1975). These investigators indicated that fastener characteristics such as length, diameter, head size, thread angle, thread diameter, and thread depth all influence joint performance.

Longer nails have greater depths of penetration over a constant deck board thickness, providing for greater withdrawal stiffness depending on the thread characteristics. Helically threaded nails are typically used in wood pallets, although annularly threaded nails and staples are used in some applications. The thread length is the effective contact area of the nail providing withdrawal resistance. Wallin (1975) determined that a high quality pallet nail requires a 0.110 inch or greater wire diameter made from medium-carbon steel (tempered or hardened) that will bend no more than 20 degrees in a MIBANT test. Nails that bend more than 20 degrees could fracture or cause splitting along the grain. Wallin and Stern (1974a) also stated that the thread diameter should be at least 0.020 inches greater than the wire diameter to provide an effective contact area between the nail threads and the wood fibers. A larger head diameter distributes stresses across a larger surface area, reducing the possibility of the head pulling through the surface of the deck board.

Samarasinghe (1987) also discussed the effects of moisture content (MC) on nailed joint stiffness. Investigators such as Laech (1964), Mack (1966), and Boyd (1965) determined that pallet strength and stiffness will be reduced if pallets that are assembled in the green condition are allowed to season. Green deck board thickness will vary if allowed to season due to shrinkage from moisture loss. The varying thickness will reduce the stiffness of the nailed connection if there is a significant change in MC. Furthermore, if a green pallet is assembled using non-coated nails, corrosion will occur, weakening the nails.

One of the last influencing variables mentioned by Samarasinghe (1987) was grain direction. Nails that are driven into the end grain of a wood member displace fibers causing wood splitting and reducing the holding power of the fibers relative to the nail threads. Side grain nailing deforms the wood fibers causing increased contact area and holding power. According to The National Design Specifications (1986), side grain lateral loading on a joint is 1/3 stronger than end grain lateral loading.

5.3 Nail Withdrawal Stiffness

Specific to nail withdrawal testing, once a nail is driven into a wood member, the fibers that are not cut apply pressure to the nail shank creating frictional forces. Over time, these frictional forces diminish as relaxation of compressed wood occurs. Joints containing threaded nails are affected less by relaxation due to the contact provided by the threads (Ehlbeck, 1978). Samarasinghe (1987) also mentioned studies conducted by McLain and Stern (1978) where the withdrawal resistance was investigated for three inch long, 0.120 inch diameter, helically threaded, hardened nails in various hardwood species. It was determined in one study that the withdrawal resistance (lbs) was 1855G (G=oven dry SG).

An equation was developed by Wallin (1975) to calculate withdrawal load (WL) based on the effective contact area per inch of shank length:

$$WL = \frac{10{,}350(TD)(P)(N)(G^{2.5})}{SinTA} \qquad [9]$$

where:

P = nail shank penetration; (in)

N = number of nails

G = specific gravity

TD = thread diameter; (in)

TA = thread angle; (deg)

The separation modulus (k) was defined by Mack (1975) and was said to depend on the withdrawal resistance of the nail shank and the head pull though resistance of the deck board. Mack developed an equation for the relationship between joint separation and k.

$$k = Ad^{-0.6} \qquad [10]$$

where:

d = separation; (in)

A = a constant

5.4 Nailed Joint Rotation Modulus

Specific to joint rotation modulus testing, Samarasinghe (1987) mentioned investigators such as Loferski (1985), Kyokong (1979), and Wilkinson (1983). Wilkinson (1983) investigated the effects of material properties, fastener types on the rotation modulus of stringer pallet joints. Analog spring models were created to analyze the moment-rotation behavior of pallet joints nailed into the side grain of the connected member.

Loferski (1985) used empirically based equations to predict rotation modulus of stringer pallet joints, assuming that rotation modulus was related to a function of fastener withdrawal strength and deck board SG. Kyokong (1979) predicted that a spring with constant stiffness could be used to simulate moment rotation characteristics. Samarasinghe (1987) also mentioned investigators who developed mathematical equations predicting rotation modulus for multiple nail joints as well as bolted joints.

5.5 Literature Specific to Current Research

Samarasinghe (1987) developed theoretical and empirical models for predicting rotation modulus of block pallet joints. Based on a spring analogy representing nailed joint stiffness, head embedment, shank withdrawal, and block edge crushing tests were conducted. Different species and nailing patterns were used to assemble block pallet joints and tested for agreement with predicted results.

In relation to current research, Samarasinghe (1987) used the following equation to predict head embedment from stiffness curves:

$$K_{hp} = \frac{P}{d} \qquad [11]$$

where:

P = force on the nail head; (lbs)

d = indention of the nail head into the wood member; (in)

Samarasinghe (1987) also used an equation containing constants generated from regression models to predict head embedment stiffness from deck board SG:

$$K_{hp} = -10245 + 91632(SGd) \qquad [12]$$

where:

SG_d = deck board SG

Samarasinghe (1987) used the following equation to predict withdrawal stiffness:

$$Kwd = \frac{P}{d} \qquad [13]$$

where:

Kwd = the withdrawal stiffness; (lbs/in)

P = withdrawal force on the nail; (lbs)

d = nail shank withdrawal; (in)

The rotation modulus is the slope of the tangent to the linear portion of the moment-rotation curve (Samarasinghe, 1987). The desired testing rotation needed to measure rotation modulus is pure rotation of the deck board excluding bending and shearing of the deck board as well as edge crushing. Samarasinghe (1987) used the following equations to determine deflections due to the bending and shearing of the deck board:

$$\Delta_{bend} = PL\left(\frac{BL}{6EI} + \frac{L^2}{3EI}\right) \qquad [14]$$

$$\Delta_{shear} = PL\left(\frac{12L}{5GbdB} + \frac{6}{5Gbd}\right) \qquad [15]$$

where:

Δ_{bend} = deflection due to deck board bending; (in)

Δ_{shear} = deflection due to shear; (in)

P = load on the joint; (lb)

L = lever arm; (in)

B = width of the stringer or block; (in)

E = modulus of elasticity; (lb/in)

I = moment of inertia of the deck board $bd^3/12$; (in^4)

b,d = width and depth of the deck board; (in)

G = shear modulus of the deck board; (lb/in) = E/16

Samarasinghe (1987) used the following equation to determine deflection due to assumed rigid-body rotation:

$$\Delta_{tot} = \Delta_{nail} + \Delta_{bend} + \Delta_{shear} \qquad [16]$$

where:

Δ_{tot} = total deck board deflection; (in)

Δ_{bend} and Δ_{shear} = as in previous equations

Δ_{nail} = deflection due to assumed rigid-body rotation; (in)

To determine the rotation modulus (in-lb/radian), Samarasinghe (1987) used the following equation:

$$RM = \frac{PL^2}{\Delta nail} \qquad [17]$$

where:

RM = rotation modulus; (in-lbs/radian)

P = load on the joint; (lbs)

Δ_{nail} = deflection due to the assumed rigid body rotation; (in)

Chapter 6

Nail Joint Stiffness Test

6.1 Introduction

It is necessary to analyze the stiffness of pallet joints when modeling the overall stiffness of wooden pallets. In order to accurately model nail joint stiffness, spring constants (k-values) must be determined for each nail. This research used two different pallet joint tests to determine the k-values; joint rotation and joint withdrawal. Joint rotation tests were conducted to determine rotation modulus. To determine the rotation modulus, loads were applied to deck board sections (nailed to stationary stringer sections) causing rotation about a neutral axis.

The nail joint withdrawal stiffness is an important component when analyzing the overall stiffness of a wood pallet joint. The withdrawal stiffness relates to the interactions between the nail shank threads and the imbedded wood fibers. Withdraw stiffness is defined as "the force required to withdraw the nail shank from the wood member by a unit length" (Samarasinghe, 1987). The following sections describe how the joint rotation and withdraw tests and stiffness measurements were conducted and determined respectively throughout this research.

Experimental procedures for joint rotation testing will be discussed followed by joint withdrawal testing.

6.2 Objective

- To determine the joint rotation modulus for use in FEA modeling of pallets.
- To determine the joint withdrawal stiffness for use in FEA modeling of pallets.

6.3 Experimental Procedure (Joint Rotation)

6.3.1 Joint Component Manufacturing and MOE Testing

Prior to manufacturing and assembling the pallet joints for rotation modulus testing, it was necessary to determine the MOE of each deck board. Because the deck board segment is in bending during the rotation tests, the stiffness of each deck board component is used in an equation to determine the k-values. The same single point bending test discussed in sections 3.4.1 and 3.6.2 was used to test 25 one-half inch thick (light weight) deck boards, 13 of which were tested for rotation modulus. The half inch thick deck boards were planed from one inch to one-half inch and came from the same eucalyptus lumber used to make the test pallets in chapter 3. Deck board segments were not removed from the light duty pallets to preserve the pallets for possible retesting. Stringer sections were also planed to 1.5 inches to correspond with the stringers in light duty pallets discussed in section 3.6.

Twelve deck board components were removed from the top deck interior deck boards of pallet #4 (heavy duty) because the MOE values were already known. The stringer sections came from the same lumber used throughout this project. It was not necessary to know the MOE for the stringer components because the test arrangement holds them in a rigid manner, preventing them from bending. All rotation joint test deck board sections were cut to six and a half inch lengths and all stringers sections (light and heavy duty) were cut to six inch lengths.

6.3.2 Joint Assembly

The joint rotation test samples used the same nailing assembly and nail type as the pallet joints of the full size pallet specimens. The nail type used for joint rotation tests can be found in section 3.3 and the nailing jig used can be seen in Figure 3, section 3.4.2. All specimens used a staggered two nail assembly. Prior to driving each nail, holes were predrilled 2¼ inches into each specimen with a 0.10 inch (77% of nail thread diameter) drill bit in order to prevent wood splitting. The nails were then driven into the samples using a hammer. All nails were driven into the side grain of each stringer section until the nail heads were flush with the top surface of each deck board section. All joint rotation specimens used a staggered two nail assembly.

A straight line was drawn across the width of the bottom surface of each deck board section one inch from the end, as in Figure 29. A small hole was predrilled into the center of the line. A metal I-hook was screwed into the hole to attach an LVDT core for deflection measurements. Stacked joint rotation samples are shown below in Figure 29.

Figure 29: Photograph of stacked joint rotation samples.

Figure 30 shows a schematic of the joint rotation specimen dimensions.

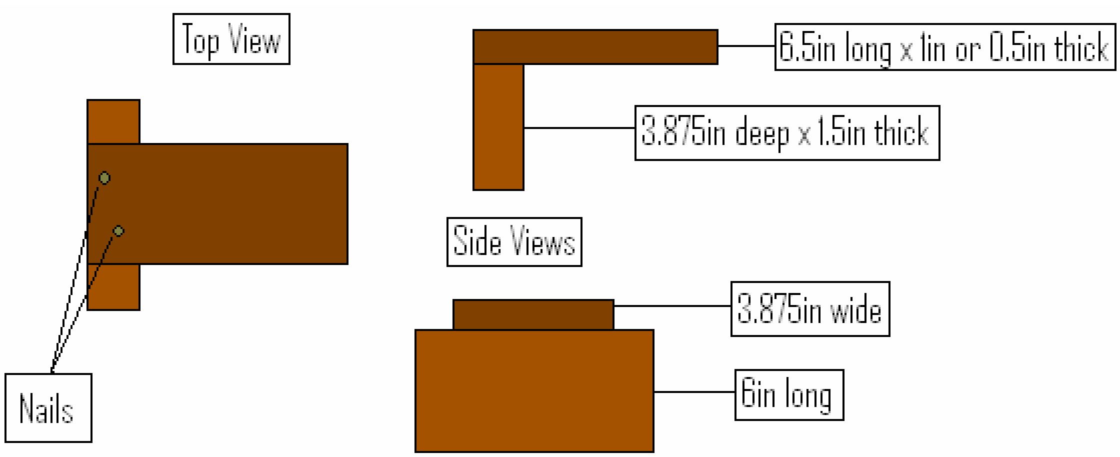

Figure 30: Schematic showing joint rotation specimen dimensions.

6.3.3 Joint Rotation Testing

All 25 joint rotation samples remained untested for 48 hours after the assembly process was complete. This gave the samples adequate time for stress relaxation, which is settlement of the wood fibers imbedded in the nail threads.

The joint rotation test set up was similar to that used by Samarasinghe (1987). The test set up was assembled using the same MTS machine that was used to test all components for MOE. A 1000 pound Interface load cell was used to measure the loads applied to each specimen. Two, LVDTs (+/- two inch travel) were used to measure deflection. One was located on the top surface of the deck board over the neutral axis of the stringer joint and the other was located underneath the bottom surface of the deck board, one inch from the end. The spring loaded LVDT located over the neutral axis of the pallet joint was used to measure the amount of vertical deflection as the deck board rotated around the edge of the stringer. The other LVDT was mounted on the bottom surface of the deck board and was used to measure the vertical deformation of the deck board as the MTS machine applied the load. A dial gauge (0.01 inch accuracy) was used to verify that each specimen was secured in a fixed location. The dial gauge was held in place using a lab clamp stand magnetically fastened to the table. The dial gauge was used to measure the amount of movement relative to the side of each stringer (shown in Figure 31).

In joint rotation tests, it is important to completely secure the specimen, eliminating any movement that would result in non-rotation deflections. All specimens were secured to the MTS table by bolting two L-brackets to the MTS table, compressing the sample in a fixed location, and using C-clamps to reinforce the L-brackets. Load was applied continuously to each specimen using a 0.1in/min deflection rate. Each test was stopped when the load stopped increasing indicating that the specimen had reached it's maximum load capacity. The pallet joint rotation test set up is shown below in Figure 31.

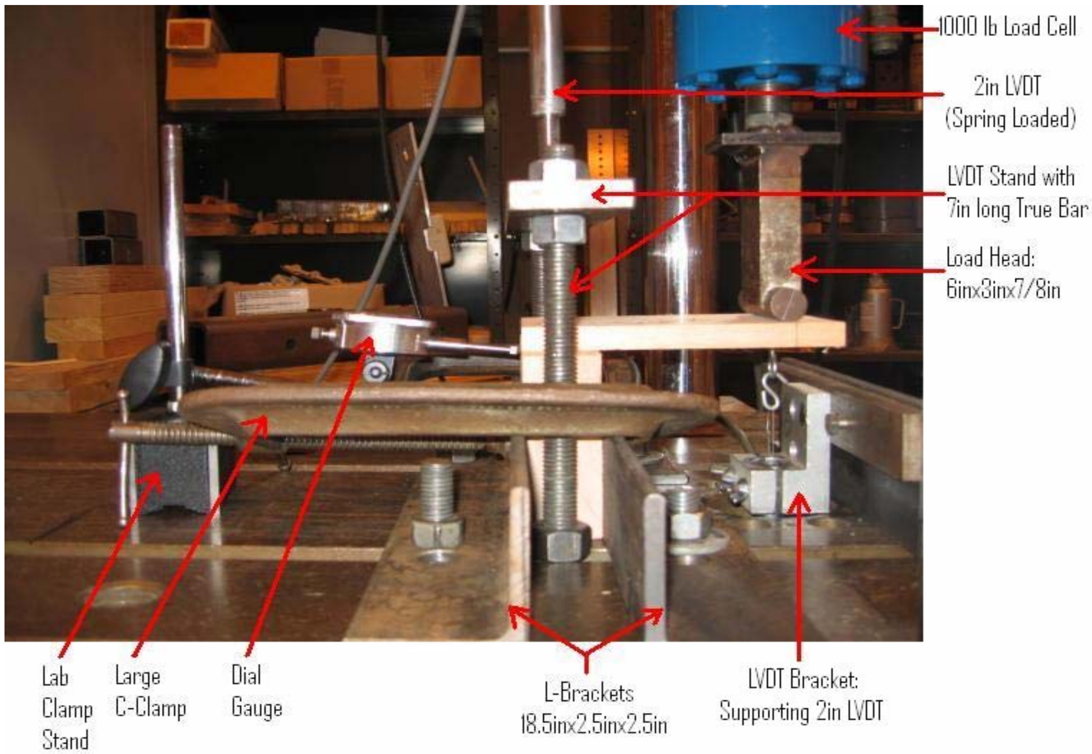

Figure 31: Photograph of the joint rotation test set up.

Prior to each joint rotation test, the load cell and the LVDTs were zeroed and the geometry of the test set up was checked for accurate alignment.

6.3.4 Computation of the Rotation Modulus

After all joint rotation tests were complete, rotation-load graphs were made to analyze the results of each test. Figure 32 shows an example rotation-load graph for a heavy duty joint rotation test.

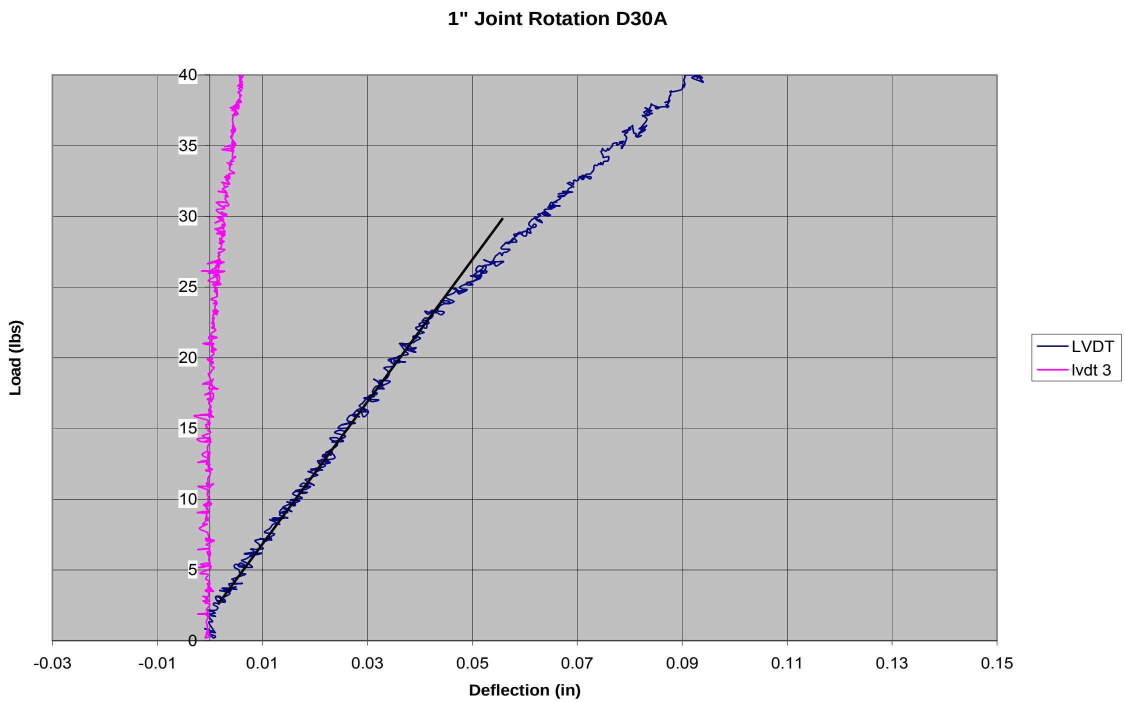

Figure 32: Graph showing rotation-load plot for a heavy duty joint rotation specimen.

The rotation modulus was computed using equations from research conducted by Samarasinghe (1987). “The rotation modulus is the slope of the tangent to the linear portion of the moment-rotation curve” (Samarasinghe, 1987). In order to determine the rotation modulus, the deflection due to bending and shear of the deck board must be calculated by:

$$\Delta_{bend} = PL\left(\frac{BL}{6EI} + \frac{L^2}{3EI}\right) \qquad [18]$$

$$\Delta_{shear} = PL\left(\frac{12L}{5GbdB} + \frac{6}{5Gbd}\right) \qquad [19]$$

where:

Δ_{bend} = deflection due to deck board bending; (in)

Δ_{shear} = deflection due to shear; (in.)

P = load on the joint; (lb.)

L = lever arm; (in.)

B = width of the stringer or block; (in.)

E = modulus of elasticity; (lb./in.^{2})

I = moment of inertia of the deck board bd^3/12; (in.^4)

b,d = width and depth of the deck board; (in.)

G = shear modulus of the deck board; (lb./in.) assumed to equal E/16

The deflection from bending and shear of the deck board must be accounted for in order to calculate pure joint rotation. The joint rotation tests conducted in this research did not account for edge crushing of the stringers. After each test was complete, the specimens were examined for any edge crushing. None of the specimens contained observable edge crushing.

After the deflections due to deck board bending and shear were determined, the deflection due to the assumed rigid-body rotation, or Δ_{nail} was calculated for each specimen. The equation used to calculate the unknown, Δ_{nail}, is given below.

$$\Delta_{tot} = \Delta_{nail} + \Delta_{bend} + \Delta_{shear} \qquad [20]$$

where:

Δ_{tot} = total deck board deflection; (in)

Δ_{bend} and Δ_{shear} = as in equations 9 and 10; (in)

Δ_{nail} = deflection due to assumed rigid-body rotation; (in)

The total deck board deflection for each specimen was measured during each joint rotation test. The two LVDTs shown in Figure 31 were separately used to measure Δ_{tot}. However, the LVDT located over the joint were not used to determine rotation modulus because non-measurable deflections were recorded. At the same load, deflections recorded by the LVDT located over the joint were one third of the other LVDT, rendering the ability to calculate realistic rotation modulii.

After Δ_{nail} was determined, the rotation modulus for each specimen was calculated using the following equation:

$$RM = \frac{PL^2}{\Delta nail} \qquad [21]$$

where:

RM = rotation modulus; (in-lbs/radian)

P = load on the joint; (lbs)

Δ_{nail} = deflection due to the assumed rigid body rotation; (in)

The following provides sample rotation modulus calculations for a heavy duty pallet joint rotation test using equations [18], [19], [20], and [21]:

$$\Delta_{bend} = 15*4\left(\frac{1.75*4}{6*1945375*0.328} + \frac{4^2}{3*1945375*0.328}\right) = 0.0006\text{ in.} \quad [22]$$

$$\Delta_{shear} = 15*4\left(\frac{12*4}{5*121586*3.94*1*1.75} + \frac{6}{5*121586*3.94*1}\right) = 0.0008\text{ in.} \quad [23]$$

$$0.035\text{in} = \Delta\text{nail} + 0.0006\text{in} + 0.0008\text{in.} \quad [24]$$

$$\Delta\text{nail} = 0.034\text{in.}$$

$$RM = \frac{15*4^2}{0.034} = 7153.3 in. - lbs / radian \quad [25]$$

6.3.5 Computation of Moisture Content (MC) and Specific Gravity (SG)

After the rotation modulus testing was complete, a small cube approximately one cubic inch was removed from each stringer and deck board section for moisture content (MC) and specific gravity (SG) measurements. An electric balance (accuracy: 0.001g.) was used to take mass measurements of each cube before (wet mass) and after (dry mass) being placed in a 103°C oven for 24 hours. These two mass measurements were used to calculate the MC of each component by subtracting the dry mass from the wet mass and then dividing by the dry mass. After the MC was calculated, the cubes were immediately dipped in a wax bath and submerged into a container of water placed upon the electric balance. The amount of water displaced by each wax coated cube was measured by the balance. The SG for each component was calculated by dividing the dry mass over the volumetric displacement. The average MC and SG for all joint rotation deck board sections were 11.19% and 0.48 respectively. The average MC and SG for all joint rotation stringer sections were 13.62% and 0.42 respectively.

The same methodology was used to determine the MC and SG of joint withdrawal specimens discussed in Section 6.5.3.

6.4 Results and Discussion

Joint rotation test data was obtained from the computer data acquisition system and processed. The rotation modulus was then calculated for each specimen. The results from all rotation test data can be found in Appendix B, Table 4. In Table 8 below, the average joint rotation modulus, SG, and MC for the half inch thick Eucalyptus, one inch thick Eucalyptus are shown. For comparison the 0.75 inch thick Yellow-poplar (Liriodendron tulipifera) data reported by Samarasinghe (1987) is also included in Table 15.

Table 15: Average joint rotation modulus, SG, and MC.

Joint Rotation (Side Grain, 2 Nails)							
Specimen	Replications	SG		MC (%)		RM(in-lbs/rad)	
		Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
0.5in Eucalyptus	12	0.48	11.1	12.8	25.0	12907	41.3
1in Eucalyptus	12	0.42	8.7	12.0	17.4	6758	19.8
0.75in Y. Pop	20	0.45	5.2	126.2	9.2	13100	29.5

Results from Table 15 show that the average rotation modulus is similar for the half inch thick Eucalyptus and 0.75 in Yellow-poplar tests. However, the average rotation modulus for the one inch thick Eucalyptus tests was approximately half as stiff as the thin specimens. The difference in stiffness between the half inch and one inch thick Eucalyptus rotation modulii is caused by the difference in nail depth penetration. Because the same nail was used to assemble all joint rotation specimens for this research, the depth of penetration for the one inch specimens was 1.25 inches and 1.75 inches for the half inch specimens. Deeper nail shank penetration results in increased surface area for the wood fibers to imbed into and around the nail threads, causing the joint to be stiffer when subjected to rotational loads. Samarasinghe's average rotation modulus is based on an average of two different nail types. She tested joint rotation specimens nailed together with 2.25 inch (.112 inch wire diameter) and 3 inch (.120 inch wire diameter) nails. It is apparent that if Samarasinghe's results were based on only the specimens using the 2.25 inch nail, the average rotation modulus would be between 6,000 in-lbs/rad. and 12,000 in-lbs/rad. range. For this reason, it is assumed that the rotation modulus increases as the nail depth penetration increases when the joint is subjected to rotational loads.

Samarasinghe's joint rotation specimens were tested green (MC = 126%) where specimens tested for this research were dry (MC = 12%). Wood fibers that are saturated with water are less stiff than dry wood fibers. Dry wood fibers grasp the nail shank increasing withdrawal stiffness when compared with wet wood fibers.

6.5 Experimental Procedure for Nail Joint Withdrawal Stiffness Tests

6.5.1 Joint Assembly

All joint withdrawal test samples were assembled using materials from the same Eucalyptus lumber used for all other tests conducted in this research. The joint withdrawal test samples were assembled using the same nailing method and nail type as used for the pallet joints. The nail type used to assemble the joint withdrawal tests can be found in section 3.3 and the nailing jig used can be found in Figure 5, section 3.4.2. The size of the deck board sections used to make the heavy duty joint withdrawal specimens was 8in x 3⅞in x 1in and the stringer sections were 7in x 3⅞in x 1½in. The light weight joint withdrawal specimens were assembled using half inch thick deck board sections and the length and width were the same as for the heavy duty specimens.

Each deck board section was centered on top of each stringer section before the specimen was predrilled. Prior to driving each nail, holes were predrilled 2¼ inches into each specimen with a 0.10 inch (77% of nail thread diameter) drill bit in order to prevent wood splitting. The nails were then driven into the samples using a hammer. All nails were driven into the side grain of each stringer section until the nail heads were flush with the top surface of each deck board section. All joint withdrawal specimens used a staggered two nail assembly.

After each joint withdrawal specimen was assembled, a centerline was drawn across the thickness of the stringer section on the edge opposite to the deck board. A ⅛ inch diameter hole was then drilled ⅝ of an inch into the center of the centerline in order to secure the LVDT bracket to each test specimen. Figure 33 below is a photograph of the joint withdrawal test specimens prior to testing.

Figure 33: Photograph showing the joint withdrawal test specimens.

Figure 34 shows a schematic of the joint withdrawal test specimen dimensions.

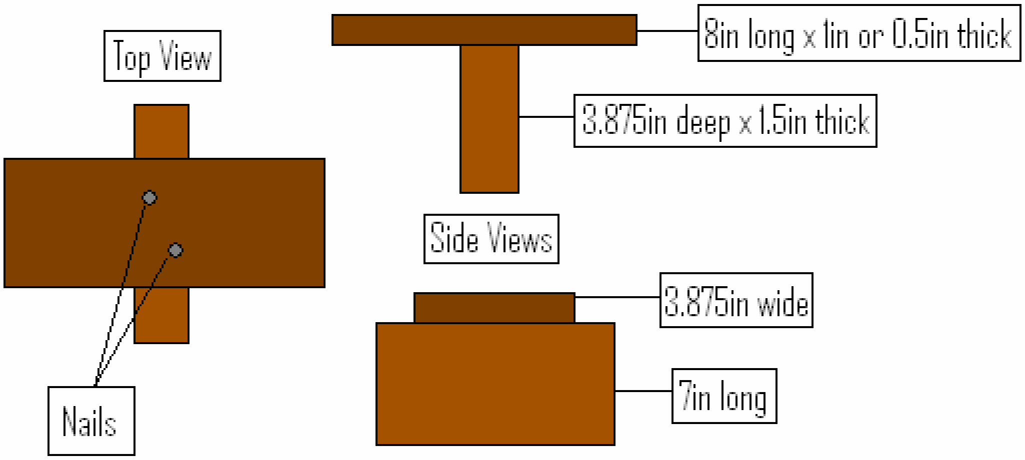

Figure 34: Schematic showing dimensions of the joint withdrawal test specimens.

6.5.2 Joint Withdrawal Testing

Twelve heavy duty and 12 light weight joint withdrawal specimens were assembled and tested in this research. All 24 joint withdrawal test specimens remained untested for 48 hours after the assembly process was complete. This gave the samples time for stress relaxation, which is settlement of the wood fibers imbedded in the nail threads.

The joint withdrawal test set up was modeled after research conducted by Samarasinghe (1987). The test set up was assembled using a 10 GL electrical-mechanical MTS machine with a 10,000 pound MTS load cell. Each test specimen was placed on top of two steel I-beam sections with the deck board section in between the I-beams and the stringer section supported by the I-beams. The test machine load head applied the load to each test specimen through a stool shaped wooden fixture. The wooden fixture had a top section with four longer sections screwed under all four corners (test component dimensions given in Figure 35). The load fixture applied the load to the deck board surface while providing space for the stringer section and the two Trans-tek LVDTs. The joint withdrawal test component dimensions are given in Figure 35.

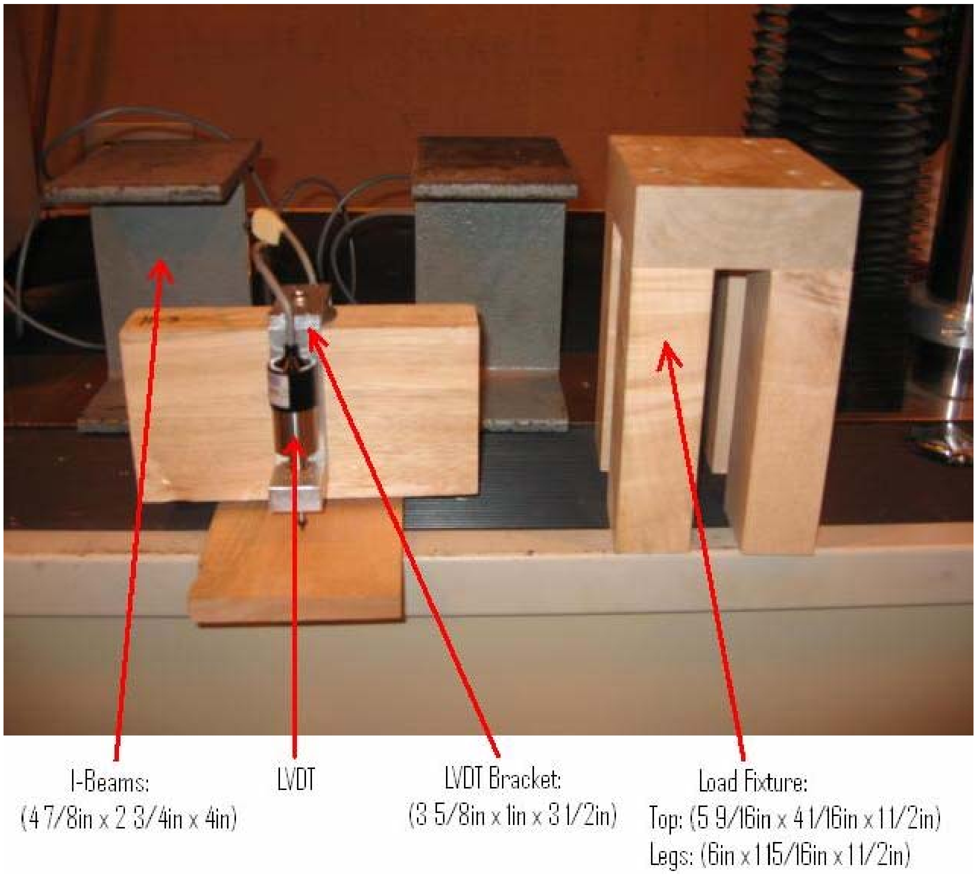

Figure 35: Photograph of the joint withdrawal test components.

The LVDTs were screwed into an aluminum bracket that was mounted to the top edge of the stringer section. As the load was applied to the deck board, the LVDTs measured the amount of deformation as the nails withdrew from the stringer. A continuous load was applied to each specimen using a 0.2in/min deflection rate. Each test was stopped when the load stopped increasing. The joint withdrawal test set up is shown in Figure 36.

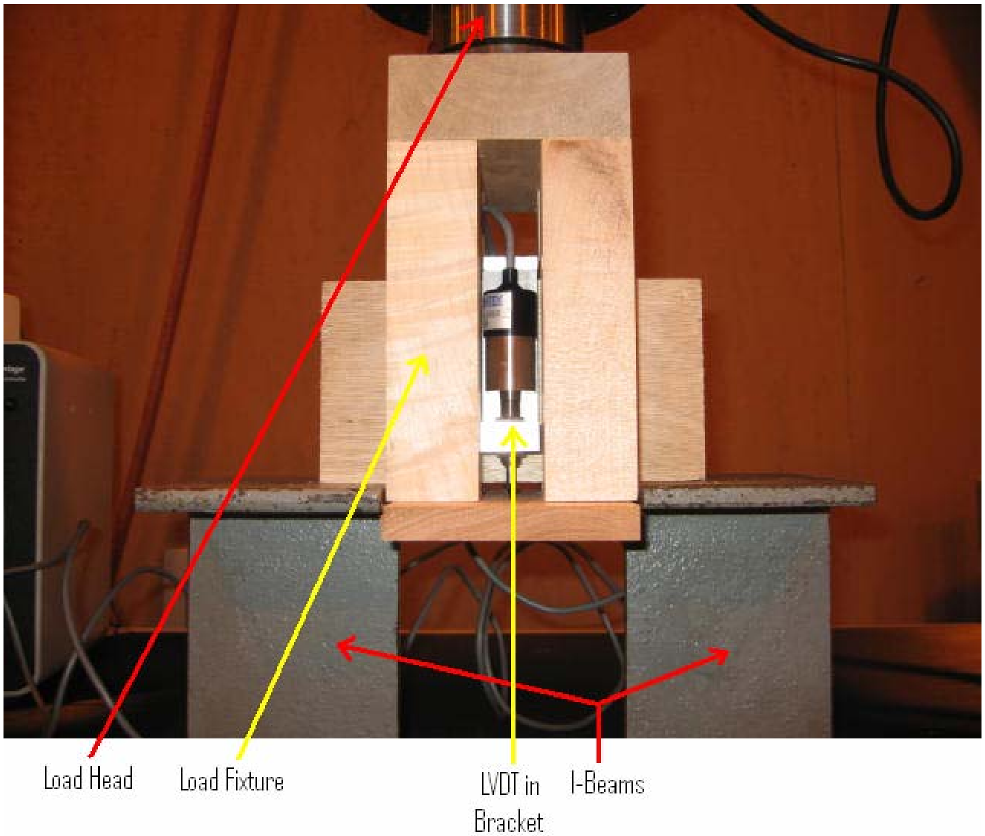

Figure 36: Photograph of joint withdrawal test set up.

6.5.3 Computation of Joint Withdrawal Stiffness

The joint withdrawal stiffness (K_{wd}) was determined using equations from research conducted by Samarasinghe (1987). Withdrawal stiffness is the "force required to withdrawal the nail shank from the wood member by a unit length" (Samarasinghe, 1987). The stiffness of a wood joint depends on the interactions between the nail shank and the wood fibers. The following equation was used to determine joint withdrawal stiffness.

$$K_{wd} = \frac{P}{d} \qquad [26]$$

where:

K_{wd} = the withdrawal stiffness (lbs/in)

P = withdrawal force on the nail (lbs)

d = nail shank withdrawal (in)

Both the withdrawal force and the nail shank withdrawal were determined from the load-deflection curve created by each test. Each curve has a linear and nonlinear portion. Only the linear portion of each curve was used to determine withdrawal stiffness to follow current pallet design procedures. Two load measurements and two deflection measurements were recorded from the linear portion of each load-deflection curve. The difference between the two load measurements and the two deflection measurements (P and d respectively) were used to determine withdrawal stiffness. Figure 37 shows a load-withdrawal curve obtained from a joint withdrawal test.

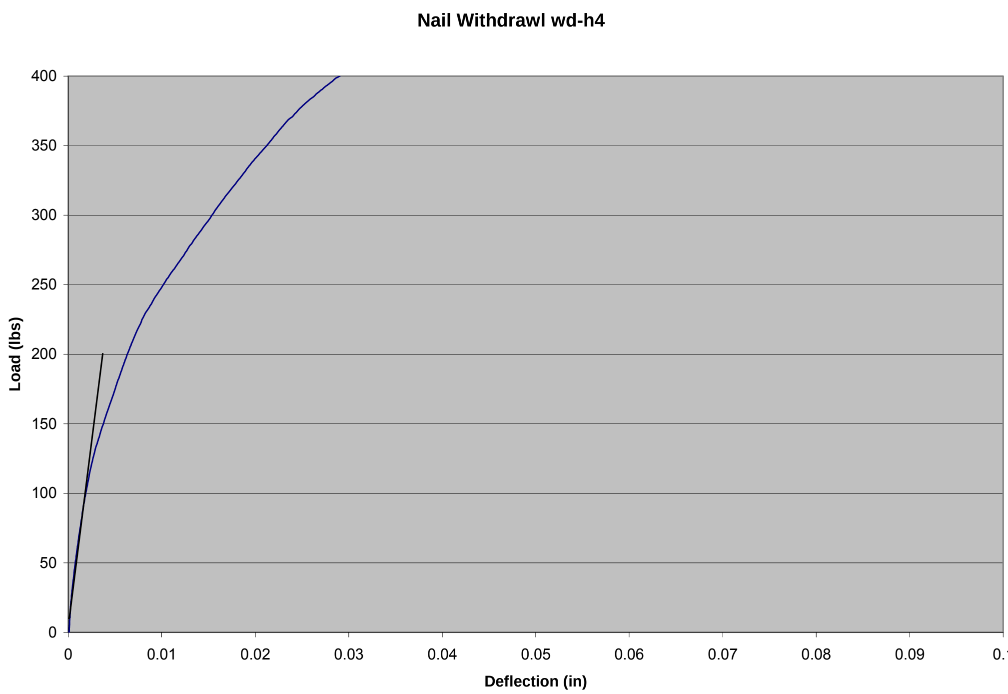

Figure 37: Graph showing the load-deflection curve for a joint withdrawal test.

After the stiffness was calculated for each joint withdrawal test sample, a one inch cube was cut from each deck board and stringer component. The cubes were used to determine the moisture content (MC) and specific gravity (SG) of each deck board and stringer component (described in Section 4.2.3). The average MC and SG for all joint withdrawal deck board sections were 8.34% and 0.46 respectively. The average MC and SG for all joint withdrawal stringer sections were 10.17% and 0.42 respectively.

6.6 Results and Discussion

Joint withdrawal test data was obtained from the computer data acquisition system and processed. The average deflection recorded by the two LVDTs was plotted against the corresponding load. Using the methodology described above in Section 6.2.3, the withdrawal stiffness of each test sample was determined. The results from this research were then compared with results from research conducted by Samarasinghe (1987). All joint withdrawal test results can be found in Appendix B, Table 5.

Table 16: Average nail withdrawal stiffness, SG, and MC.

Nail Withdrawal (Side Grain, 2 Nails)							
Specimen	Replications	SG		MC (%)		Kwd(lb/in)	
		Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
0.5in Eucalyptus	12	0.44	8.71	7.63	25.75	44008	25.16
1in Eucalyptus	12	0.43	7.05	10.88	13.78	57823	35.20
0.75in Y. Pop	20	0.44	5.22	126.2	9.2	26803	25.2

Research conducted by S. Samarasinghe (1987) investigated the withdrawal of block style pallet joints in both the side grain and end grain of three different wood species using both 2.25 inch and 3 inch nails. Table 16 shows the average specific gravity (SG), moisture content (MC), and withdrawal stiffness (Kwd) for half inch (light duty) and one inch (heavy duty) thick Eucalyptus specimens along with 0.75 inch Yellow-poplar withdrawal specimens from Samarasinghe's research. The average SG was very similar for the specimens tested. However, the moisture contents were not similar. Samarsinghe (1987) tested specimens containing green (saturated) components where this research used kiln dried specimens. The difference in MC reflects upon the average Kwd results. The drier Eucalyptus specimens yielded higher average joint withdrawal stiffness than the green Yellow-poplar. A statistical difference is apparent when comparing the average Eucalyptus joint stiffness with the average Yellow-poplar joint stiffness. Factors affecting the joint withdrawal stiffness include the nail type and depth penetration, component SG, and component MC. The difference in MC between Eucalyptus and Yellow-poplar test specimens is most likely the reason for the difference in joint withdrawal stiffness. The Yellow-poplar specimens yielded lower average withdrawal stiffness because green wood fibers are not as stiff as dry wood fibers in species of similar SG. Therefore, the green Yellow-poplar fibers were not able to grip the nail threads as well as the dry Eucalyptus fibers, yielding lower average joint withdrawal stiffness.

Chapter 7

Summary, Conclusions, Recommendations, and Limitations

7.1 Summary

The affect of different designs and support conditions on pallet stiffness were investigated in this research. Pallet test data was developed by applying uniform loads to six different pallet designs supported in six different conditions. Specifically, nine heavy duty and three light duty pallets with three, four, and five stringer designs were tested in the RAL, RAW, non-notched fork tine, notched fork tine, top deck floor stack, and bottom deck floor stack support conditions. All test specimens were assembled using virtually identical materials. All pallet components were tested for MOE in order to determine the overall stiffness of each pallet specimen.

Uniform test loads were applied to each pallet specimen. Pallet bending tests used string pots to measure deflections in three different locations. Test machine compliance was taken into account using an LVDT to adjust the measured deflections.

Pallet joints were made using the same materials and assembly process. Joint rotation and joint withdrawal tests were conducted to determine rotation modulus and withdrawal stiffness respectively. The rotation modulus and withdrawal stiffness measurements were used to understand pallet joint stiffness.

Measured and predicted pallet bending results were compared to determine the percent error in structural model predictions.

7.2 Conclusions

The specific conclusions are summarized as follows:

1. Heavy duty pallets were, on average, 6.5 times stiffer than light duty pallets in RAW bending tests, supporting the hypothesis that thicker deck boards produce stiffer pallets. Increased component thickness causes higher moment of inertia thus increasing pallet stiffness.

2. The overall average stiffness for all heavy duty RAL pallet bending tests was reduced by 51% after notching, supporting the hypothesis that notched pallets are less stiff than non-notched pallets. Non-notched stringers have greater moments of inertia making them stiffer than notched stringers. The notch fillet is a critical stress location that is the origin of wood splitting in notched pallet RAL support conditions.

3. Light duty pallets were less stiff than the heavy duty pallets in non-notched fork tine support conditions. The average stiffness of 3, 4, and 5 stringer light duty pallets were 39%, 46%, and 60% less stiff than heavy duty pallets respectively, when tested with the fork tine support between the deck boards.

4. Pallet stiffness decreased as the fork tine support span increased. The average fork tine support pallet stiffness decreased by 29% and 49% for four and five stringer pallets respectively, compared to three stringer.

5. Average notched fork tine support pallet stiffness decreased by 29% and 3% for four and five stringer pallets respectively, compared to three stringer pallets.

4. ANSYS structural model estimates had lower percent errors for light duty pallet bending tests than heavy duty pallet bending tests. The average predicted error for heavy duty and light duty pallet bending tests were 13% and 3% respectively. All pallet specimens were assembled using component stiffness (MOE) gradients, making one end or side of each pallet stiffer than the other. Predicted results were based on pallet models using average stiffness for each of the different component types. Experimental error could have resulted in the application of a non-uniform load. The semi-rigid air bag load may have caused the load to bridge across the pallet surface.

5. The average predicted error for ANSYS structural analyses was less than the average predicted error for PDS structural analyses. The PDS average deflection prediction errors for heavy duty and light duty pallets were 23% and 14% respectively.

6. Heavy duty pallet joints were approximately half as stiff in rotation as light duty pallet Joints because the depth of nail shank penetration was less in the thicker heavy deck boards then the light duty deck boards. The average heavy duty joint rotation modulus was 6758 in-lbs/radian and the average light duty joint rotation modulus was 12907 in-lbs/radian.

7. Light duty pallet joints were less stiff in withdrawal than heavy duty pallet joints. The average joint withdrawal stiffness for light duty pallet joints was 44008 lbs/in and the average joint withdrawal stiffness for heavy duty joints was 57823 lbs/in. The average heavy duty joint withdrawal stiffness was greater than the average light duty joint withdrawal stiffness because the half inch thick deck boards would bend when loaded.

7.3 Project Limitations

The limitations of the project results include:

1. Pallets with one inch and one half inch thick Eucalyptus deck boards and one and three quarter inch and one and a half inch thick Eucalyptus stringers were tested.
2. Pallets with nine inch long, one and a half inch deep, and half inch fillet radii notches were tested.
3. Uniform loads were applied to test pallets.
4. RAL (44in span), RAW (36in span), fork tine (even spacing), and top and bottom floor stack (fully supported) support conditions were used.
5. Specific test loads were applied to test pallets in the linear range of pallet response.
6. Non-destructive pallet tests were conducted.
7. Joint rotation and joint withdrawal test specimens were one inch thick and one half inch thick deck boards joined, using nails of the same specification, to one and three quarter inch thick and one and one half inch thick stringers.
8. One inch and one half inch joint stiffness specimens were tested.

7.4 Recommendations for Future Research

Recommendations for future use include:

1. Higher bending test deflections are recommended due to limitation of the sensitivity of deflection measurement devices.
2. Test pallets assembled with randomized placement of component stiffness.
3. Joint stiffness tests including edge crush and head embedment stiffness measurements.
4. Similar research investigating block pallet performance.
5. Different size pallets should be tested.
6. ANSYS models should include notched stringers.

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Appendix A

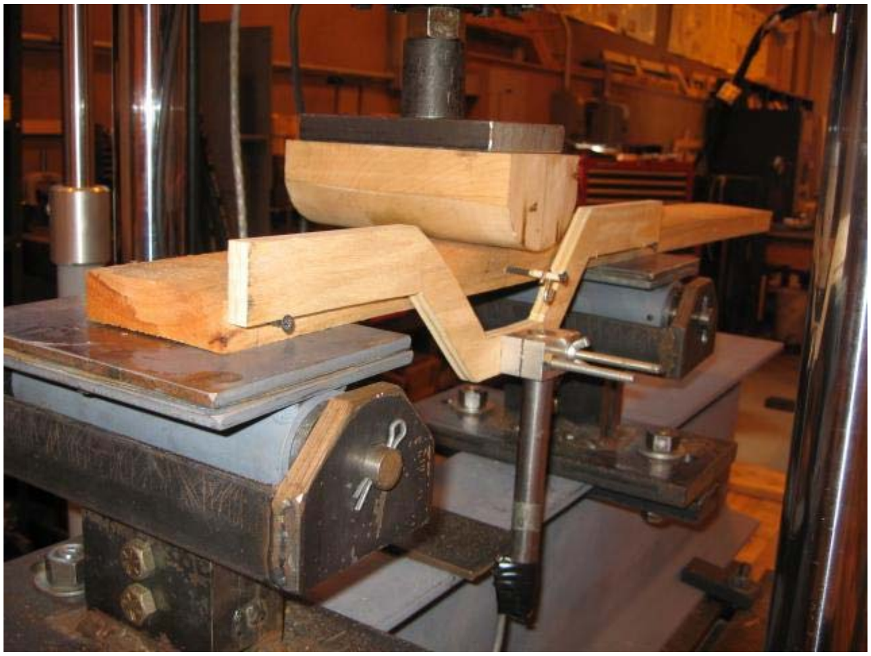
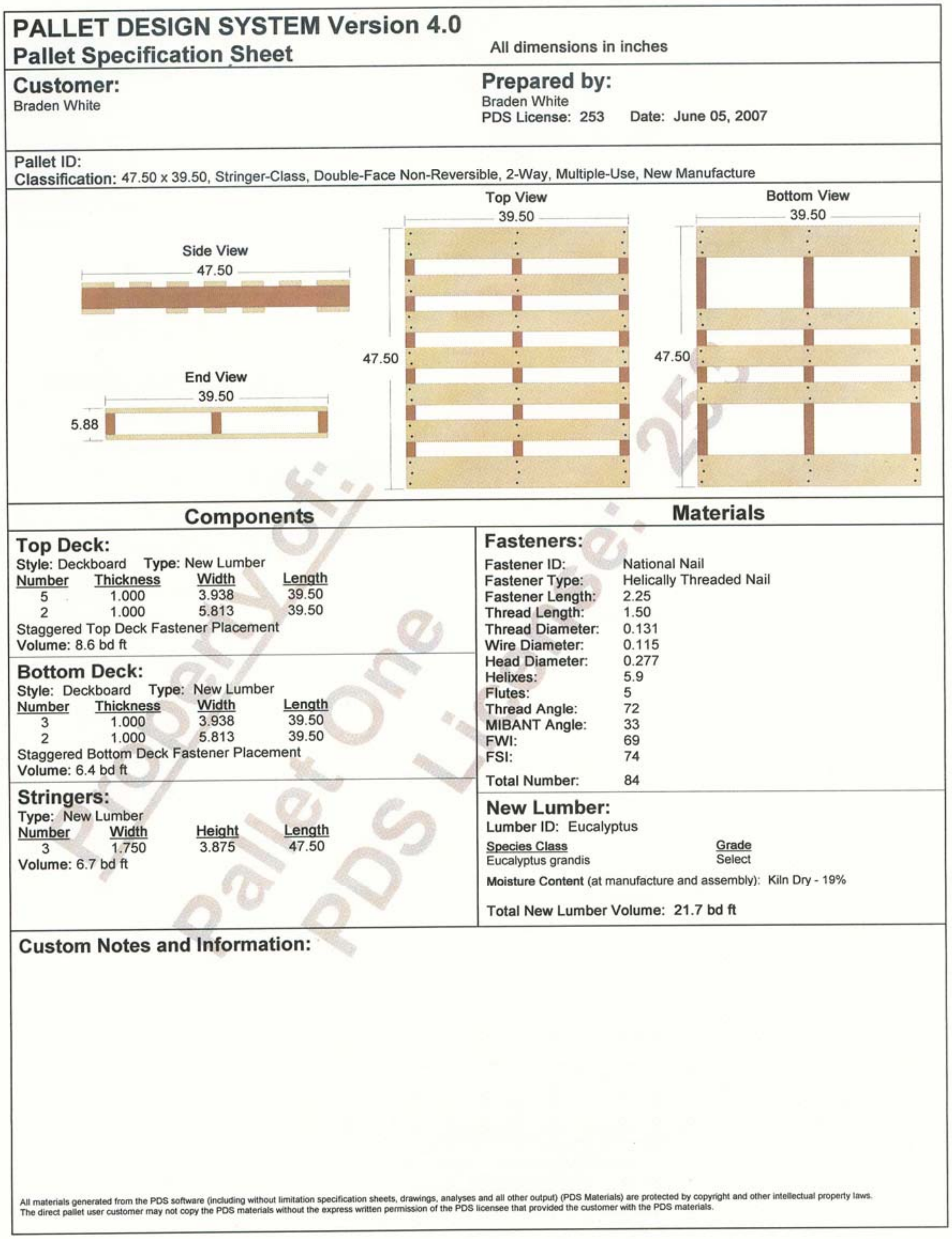


Figure 1: Picture showing single point bending test for deck board MOE.



PALLET DESIGN SYSTEM Version 4.0
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: June 05, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture

Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 6.4 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
3	1.750	3.875	47.50

Volume: 6.7 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	84

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 21.7 bd ft

Custom Notes and Information:

Figure 2: Heavy duty 3 stringer pallet design details (used with permission of PalletOne).

PALLET DESIGN SYSTEM Version 4.0

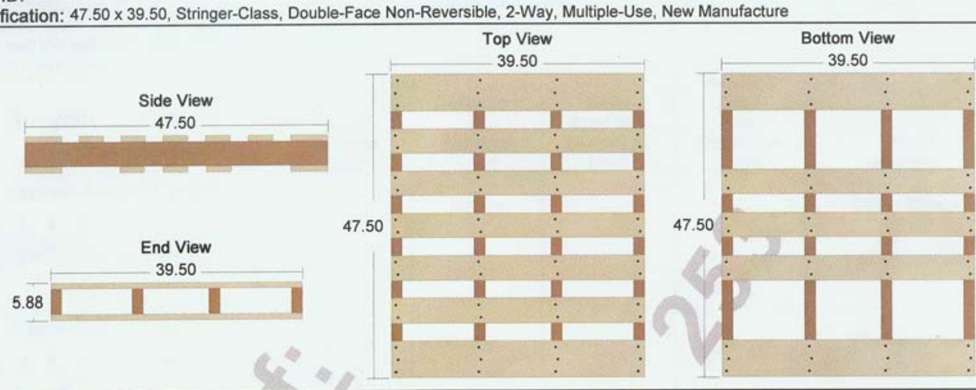
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: June 05, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 6.4 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
4	1.750	3.875	47.50

Volume: 8.9 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	112

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 24.0 bd ft

Custom Notes and Information:

Figure 3: Heavy duty 4 stringer pallet design details (used with permission of PalletOne).

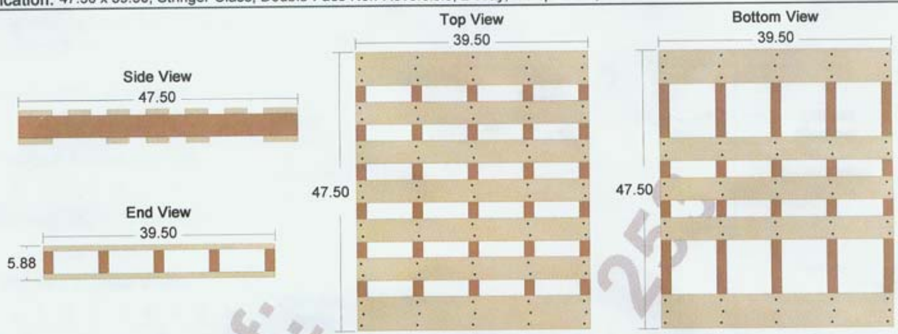
PALLET DESIGN SYSTEM Version 4.0
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: June 05, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 6.4 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
5	1.750	3.875	47.50

Volume: 11.2 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	139

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 26.2 bd ft

Custom Notes and Information:

Figure 4: Heavy duty 5 stringer pallet design details (used with permission of PalletOne) .

PALLET DESIGN SYSTEM Version 4.0

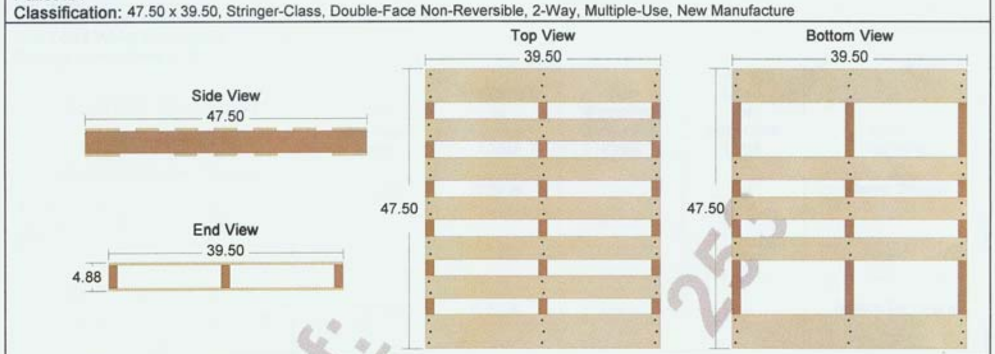
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: September 19, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 4.3 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 3.2 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
3	1.500	3.875	47.50

Volume: 5.8 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	84

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 13.3 bd ft

Custom Notes and Information:

Figure 5: Light duty 3 stringer pallet design details (used with permission of PalletOne) .

PALLET DESIGN SYSTEM Version 4.0

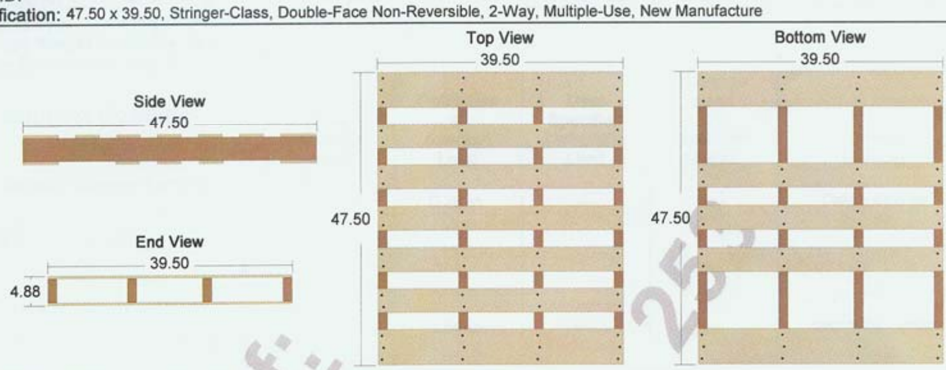
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253   Date: September 19, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard   Type: New Lumber

Number	Thickness	Width	Length
5	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 4.3 bd ft

Bottom Deck:
Style: Deckboard   Type: New Lumber

Number	Thickness	Width	Length
3	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 3.2 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
4	1.500	3.875	47.50

Volume: 7.7 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	112

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 15.2 bd ft

Custom Notes and Information:

Figure 6: Light duty 4 stringer pallet design details (used with permission of PalletOne).

PALLET DESIGN SYSTEM Version 4.0

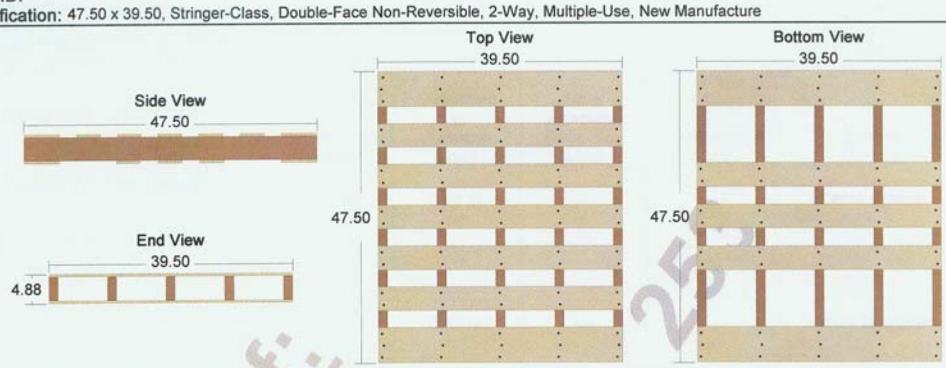
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: September 19, 2007

Pallet ID:
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, 2-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 4.3 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	0.500	3.938	39.50
2	0.500	5.813	39.50

Staggered Bottom Deck Fastener Placement
Volume: 3.2 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
5	1.500	3.875	47.50

Volume: 9.6 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	139

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

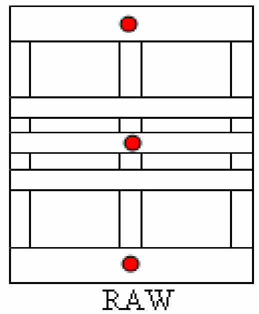
Total New Lumber Volume: 17.1 bd ft

Custom Notes and Information:

Figure 7: Light duty 5 stringer pallet design details (used with permission of PalletOne) .

Figure 8: Photograph showing the pallet assembly jig.

Figure 9: Photograph showing a heavy duty five stringer top deck assembly.



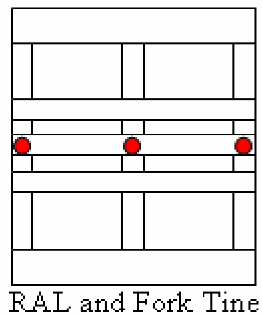


Figure 10: Diagrams showing the string pot locations for non-notched RAW, RAL, and fork tine support conditions

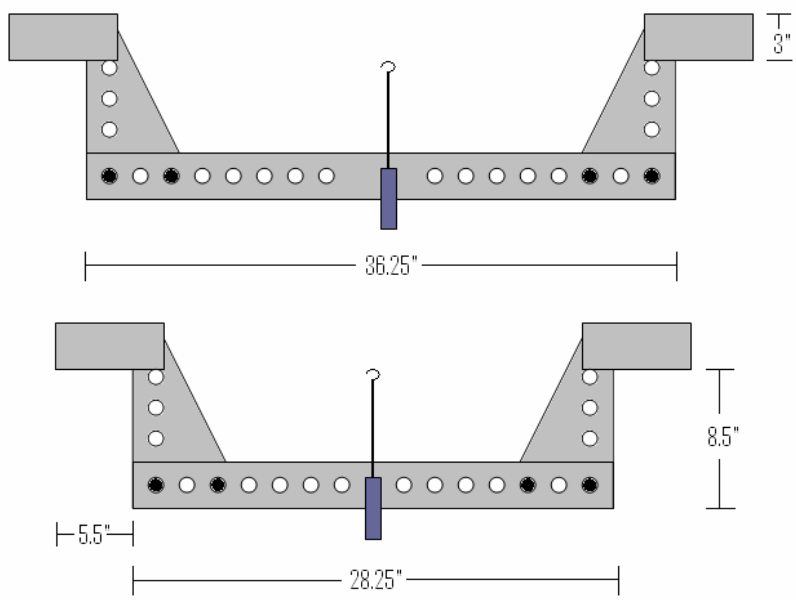


Figure 11: Diagrams showing the yoke dimensions.

Figure 12: Photograph showing the LVDT/Yoke set up for a RAL bending test.

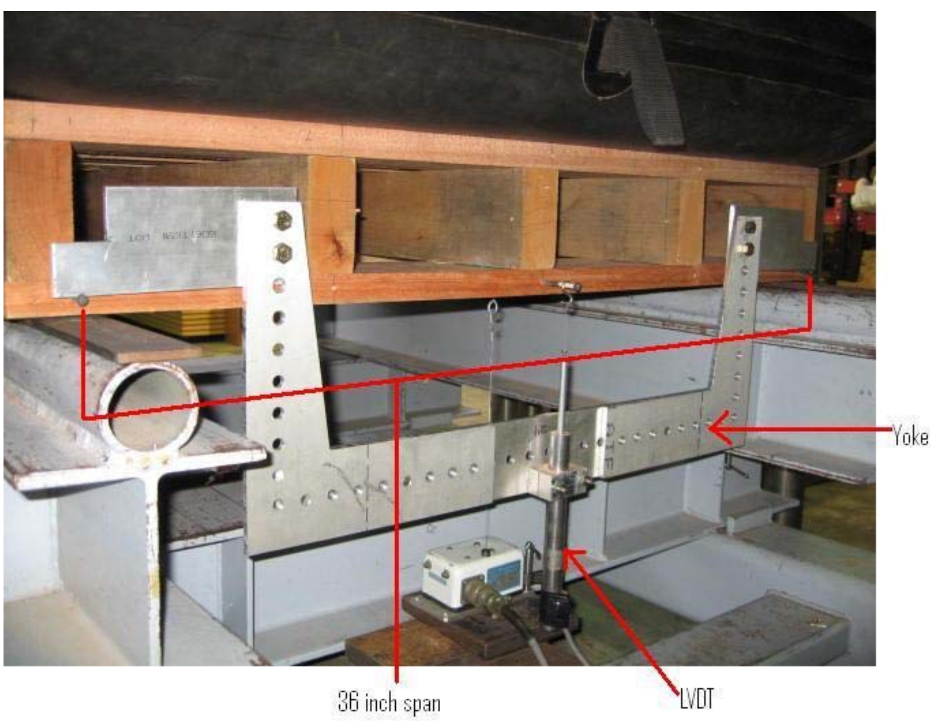


Figure 13: Photograph showing the LVDT/Yoke set up for a RAW bending test.

Figure 14: Photograph showing the LVDT set up for non-notched fork tine support bending tests.

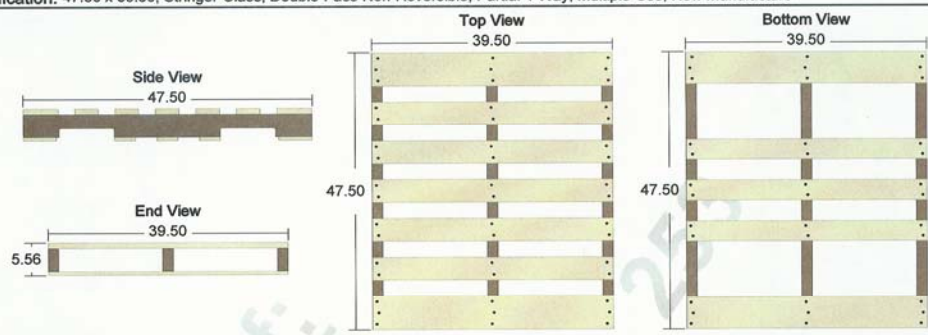
PALLET DESIGN SYSTEM Version 4.0
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: May 21, 2008

Pallet ID: Braden 48X40 P4 way 3 stringer
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	0.688	3.500	39.50
2	0.688	5.500	39.50

Staggered Bottom Deck Fastener Placement
Volume: 4.1 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
3	1.750	3.875	47.50

Partial 4-way Entry Notch:
Depth: 1.500 Length: 9.00 Location: 6.00 Radius: 0.50
Volume: 6.7 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	84

New Lumber:
Lumber ID: Eucalyptus

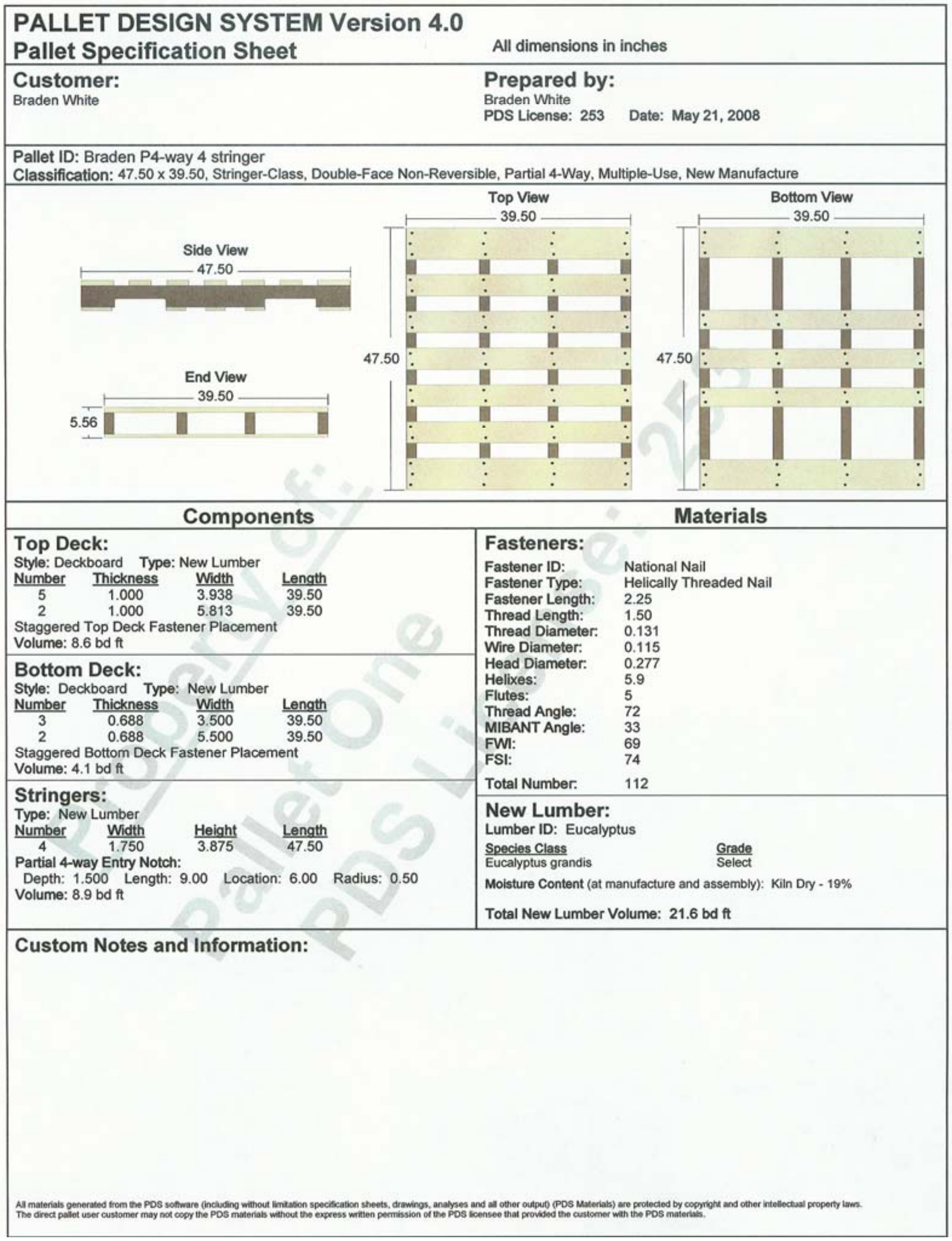
Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 19.4 bd ft

Custom Notes and Information:

Figure 15: Notched heavy duty 3 stringer pallet design details.



PALLET DESIGN SYSTEM Version 4.0
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: May 21, 2008

Pallet ID: Braden P4-way 4 stringer
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Multiple-Use, New Manufacture

Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	0.688	3.500	39.50
2	0.688	5.500	39.50

Staggered Bottom Deck Fastener Placement
Volume: 4.1 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
4	1.750	3.875	47.50

Partial 4-way Entry Notch:
Depth: 1.500 Length: 9.00 Location: 6.00 Radius: 0.50
Volume: 8.9 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	112

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 21.6 bd ft

Custom Notes and Information:

Figure 16: Notched heavy duty 4 stringer pallet design details.

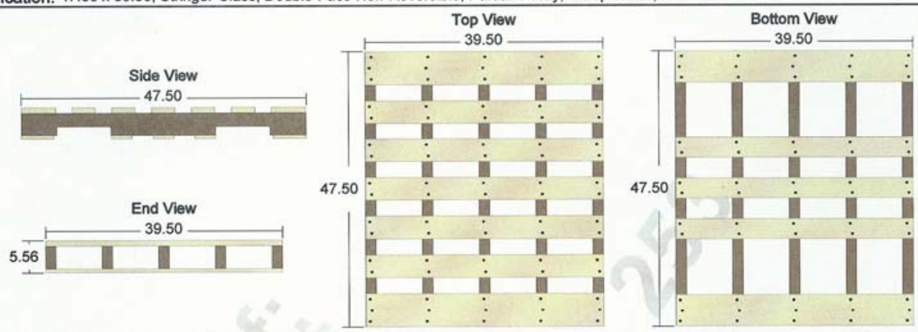
PALLET DESIGN SYSTEM Version 4.0
Pallet Specification Sheet

All dimensions in inches

Customer:
Braden White

Prepared by:
Braden White
PDS License: 253 Date: May 21, 2008

Pallet ID: Braden 48X40 P4 way 5 stringer
Classification: 47.50 x 39.50, Stringer-Class, Double-Face Non-Reversible, Partial 4-Way, Multiple-Use, New Manufacture



Components

Top Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
5	1.000	3.938	39.50
2	1.000	5.813	39.50

Staggered Top Deck Fastener Placement
Volume: 8.6 bd ft

Bottom Deck:
Style: Deckboard Type: New Lumber

Number	Thickness	Width	Length
3	0.688	3.500	39.50
2	0.688	5.500	39.50

Staggered Bottom Deck Fastener Placement
Volume: 4.1 bd ft

Stringers:
Type: New Lumber

Number	Width	Height	Length
5	1.750	3.875	47.50

Partial 4-way Entry Notch:
Depth: 1.500 Length: 9.00 Location: 6.00 Radius: 0.50
Volume: 11.2 bd ft

Materials

Fasteners:

Fastener ID:	National Nail
Fastener Type:	Helically Threaded Nail
Fastener Length:	2.25
Thread Length:	1.50
Thread Diameter:	0.131
Wire Diameter:	0.115
Head Diameter:	0.277
Helixes:	5.9
Flutes:	5
Thread Angle:	72
MIBANT Angle:	33
FWI:	69
FSI:	74
Total Number:	140

New Lumber:
Lumber ID: Eucalyptus

Species Class	Grade
Eucalyptus grandis	Select

Moisture Content (at manufacture and assembly): Kiln Dry - 19%

Total New Lumber Volume: 23.8 bd ft

Custom Notes and Information:

Figure 17: Notched heavy duty 5 stringer pallet design details.

Figure 18: Photograph showing the RAL test set up for a notched heavy duty pallet.

Figure 19: Photograph showing the RAW test set up for a notched heavy duty pallet.

Figure 20: Photograph showing the LVDT set up for a notched heavy duty fork tine support bending test.

Figure 21: Photograph showing the set up for a light duty 3 stringer bottom deck floor stack bending test.

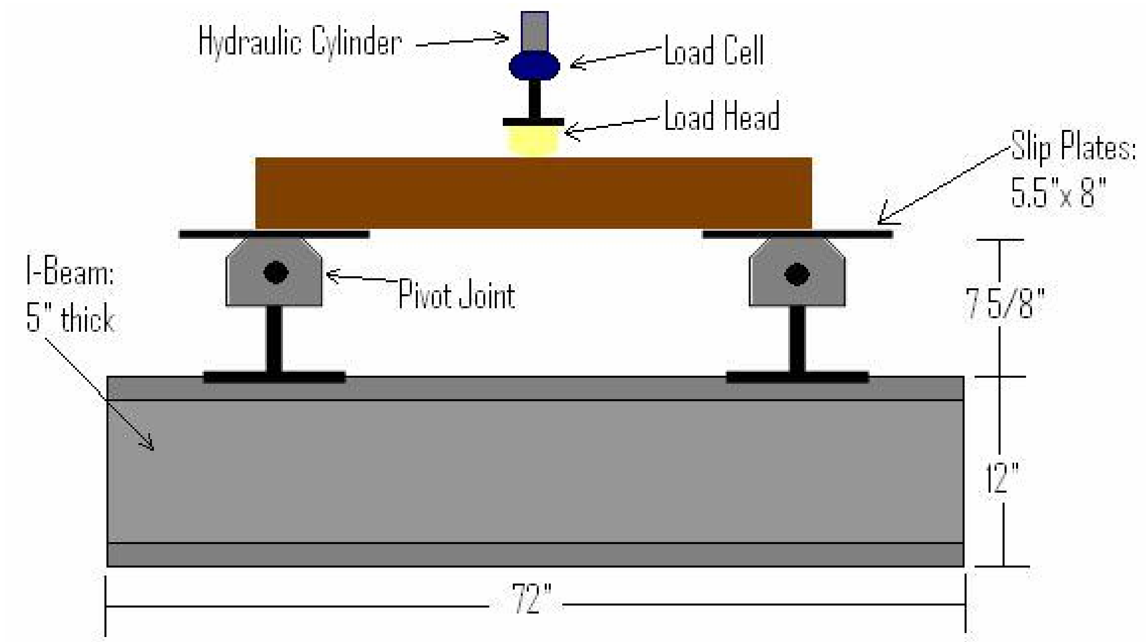


Figure 22: Diagram showing the single point bending test set up for stringer MOE.

Appendix B

Table 1: Data Table containing heavy duty pallet component MOE summary table.

Pallet #	Deckboards			Pallet #	Leadboards			Pallet #	Stringers		
	L	1562981	D72		L	1458933	L34		L	1339053	S25
	L	1602538	D22	1	L	1493435	L1	1	L	1341547	S28
	L	1630318	D43		L	1519454	L5		L	1376970	S18
1	L	1654745	D29		L	1556875	L23		L	1402068	S20
	L	1697270	D50		L	1575346	L17	2	L	1451148	S34
	L	1718784	D26	2	L	1581381	L8		L	1477545	S14
	L	1735855	D7		L	1581606	L24		L	1492504	S19
	L	1780874	D16		L	1606402	L31		L	1501352	S16
	L	1816420	D45		L	1628750	L26		L	1505250	S8
	L	1818324	D23	3	L	1646535	L29	3	L	1510644	S7
	L	1845639	D3		L	1648507	L16		L	1524787	S11
2	L	1847045	D21		L	1655009	L32		L	1530695	S22
	L	1872699	D64		M	1688658	L33		M	1554569	S29
	L	1875012	D6	4	M	1701126	L10	4	M	1560463	S31
	L	1876251	D11		M	1701344	L14		M	1562753	S1
	L	1888610	D18		M	1711691	L19		M	1600924	S30
	L	1902070	D2		M	1724124	L25	5	M	1602886	S27
	L	1908276	D62	5	M	1792135	L11		M	1654306	S24
	L	1922942	D38		M	1799924	L27		M	1657660	S36
3	L	1924213	D66		M	1818741	L13		M	1676374	S6
	L	1940360	D10		M	1861187	L21		M	1677686	S12
	L	1959741	D40	6	M	1884561	L12	6	M	1683823	S13
	L	1990641	D5		M	1912369	L20		M	1687211	S32
	L	2008879	D56		M	1912819	L35		M	1692030	S9
	M	2013829	D58		H	1950508	L18		H	1693825	S5
	M	2034880	D61	7	H	1952705	L6	7	H	1712008	S23
	M	2049657	D46		H	1982056	L36		H	1712347	S35
4	M	2071319	D30		H	2017227	L4		H	1716889	S26
	M	2076872	D13		H	2048747	L30	8	H	1743357	S4
	M	2088876	D47	8	H	2068506	L28		H	1784231	S15
	M	2107257	D48		H	2098939	L7		H	1800671	S17
	M	2110124	D17		H	2102455	L22		H	1878153	S10
	M	2116346	D27		H	2110713	L2		H	1888154	S3
	M	2143937	D31	9	H	2154034	L15	9	H	1974477	S21
	M	2153226	D19		H	2235695	L3		H	1978561	S33
5	M	2163572	D34		H	2319295	L9		H	2020021	S2
	M	2175148	D8								
	M	2193825	D4								
	M	2239593	D35								
	M	2241944	D41								
	M	2246750	D69								
	M	2270573	D60								

6	M	2285226	D42
	M	2289656	D59
	M	2292883	D65
	M	2312718	D1
	M	2317196	D20
	M	2325971	D32
7	H	2341916	D9
	H	2377216	D28
	H	2383134	D68
	H	2389020	D24
	H	2402738	D25
	H	2409946	D12
	H	2422420	D36
	H	2431772	D55
8	H	2469439	D54
	H	2480666	D53
	H	2499736	D70
	H	2526900	D63
	H	2569572	D67
	H	2574043	D49
	H	2587608	D15
	H	2615025	D44
9	H	2617224	D52
	H	2635308	D51
	H	2673966	D57
	H	2686882	D33
	H	2813712	D37
	H	2833455	D39
	H	2836302	D71
	H	2847609	D14

Table 2: Data table containing the heavy duty pallet bending test results.

(Blue=3 stringer, Green=4 stringer, Red=5 stringer)

Non Notched Racking Data								
Racked Across Length								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	2013.8480	0.1309	0.1172	0.0829	0.0444	0.0581	0.0444	0.0101
	4083.4800	0.2007	0.1667	0.1388	0.0900	0.1240	0.0900	0.0621
2	4038.032	0.169556	0.175788	0.122968	0.066576	0.0603	0.0666	0.0138
	6141.864	0.227468	0.215232	0.172976	0.102638	0.1149	0.1026	0.0604
3	4012.3440	0.1705	0.1541	0.1007	0.0604	0.0767	0.0604	0.0070
	7975.3640	0.2517	0.2244	0.1750	0.1123	0.1395	0.1123	0.0628
4	2033.3040	0.1252	0.0793	0.1067	0.0451	0.0910	0.0451	0.0725
	4062.2760	0.1984	0.1464	0.1623	0.0891	0.1411	0.0891	0.1051
5	2999.5680	0.1364	0.1137	0.0911	0.0402	0.0629	0.0402	0.0176
	5994.5760	0.2160	0.1672	0.1569	0.0817	0.1305	0.0817	0.0714
6	3998.8160	0.1393	0.1240	0.0990	0.0598	0.0750	0.0598	0.0348
	8105.3240	0.2155	0.1960	0.1566	0.1145	0.1340	0.1145	0.0750
7	2039.0800	0.1262	0.1180	0.1189	0.0375	0.0457	0.0375	0.0384
	4092.3720	0.2038	0.1759	0.1706	0.0796	0.1075	0.0796	0.0743
8	3102.5480	0.1103	0.1292	0.0907	0.0421	0.0231	0.0421	0.0035
	5427.0840	0.1724	0.1741	0.1367	0.0752	0.0735	0.0752	0.0378
9	4009.9120	0.1080	0.1075	0.0828	0.0413	0.0417	0.0413	0.0166
	8059.1920	0.1737	0.1644	0.1436	0.0856	0.0948	0.0856	0.0648

Racked Across Width								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	2051.9240	0.1307	0.1425	0.1518	0.0861	0.0743	0.0861	0.0953
	4006.8720	0.2228	0.2424	0.2411	0.1561	0.1364	0.1561	0.1548
2	2999.4920	0.1779	0.1940	0.1567	0.0985	0.0824	0.0985	0.0612
	5060.9920	0.2624	0.2886	0.2254	0.1552	0.1290	0.1552	0.0920
3	3099.3560	0.2120	0.2258	0.2005	0.1036	0.0899	0.1036	0.0783
	4420.5400	0.2679	0.2820	0.2542	0.1449	0.1308	0.1449	0.1171
4	2579.6680	0.1538	0.1741	0.1386	0.1025	0.0822	0.1025	0.0670
	3958.7640	0.2171	0.2387	0.1879	0.1514	0.1297	0.1514	0.1006
5	3000.8600	0.1651	0.1641	0.1684	0.1080	0.1091	0.1080	0.1124
	5089.7200	0.2510	0.2398	0.2636	0.1728	0.1841	0.1728	0.1966
6	3049.3480	0.1551	0.1670	0.1639	0.1012	0.0893	0.1012	0.0982
	4514.1720	0.2136	0.2042	0.2113	0.1401	0.1495	0.1401	0.1472
7	2077.3840	0.1430	0.1092	0.2064	0.0645	0.0983	0.0645	0.1617
	3542.9680	0.2211	0.1718	0.2768	0.1108	0.1601	0.1108	0.2158
8	2961.1120	0.1711	0.1819	0.1693	0.0839	0.0731	0.0839	0.0713
	5041.8400	0.2621	0.2664	0.2475	0.1349	0.1307	0.1349	0.1161
9	3092.4400	0.1365	0.1423	0.1352	0.0640	0.0582	0.0640	0.0569
	4982.1040	0.1912	0.2169	0.1781	0.1002	0.0746	0.1002	0.0615

Fork Tine Support **supports through deckboards**								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	6013.5000	0.2079	0.2216	0.2408	0.0850	0.1229	0.1366	0.1558
	8104.9440	0.2597	0.2829	0.3068	0.1089	0.1508	0.1740	0.1979
2	4038.6400	0.1665	0.1195	0.1469	0.0559	0.1106	0.0637	0.0910
	8025.6000	0.2752	0.2076	0.2388	0.0922	0.1830	0.1154	0.1466
3	4034.4600	0.1883	0.1382	0.1184	0.0549	0.1334	0.0833	0.0635
	8019.2920	0.3220	0.2126	0.1984	0.0849	0.2371	0.1277	0.1135
4	4092.5240	0.1615	0.1689	0.1774	0.0708	0.0907	0.0982	0.1066
	8033.5040	0.2610	0.2900	0.2924	0.1170	0.1440	0.1730	0.1754
5	4072.8400	0.1617	0.1266	0.1348	0.0576	0.1041	0.0690	0.0772
	8001.8880	0.2741	0.1991	0.2142	0.0927	0.1815	0.1064	0.1215
6	4032.4840	0.1770	0.1119	0.1062	0.0613	0.1157	0.0505	0.0448
	8008.6520	0.2917	0.1940	0.1874	0.0947	0.1970	0.0993	0.0927
7	4070.6360	0.1795	0.1783	0.1965	0.0639	0.1156	0.1144	0.1326
	8009.4880	0.2879	0.2859	0.3257	0.1080	0.1799	0.1779	0.2176
8	4076.6400	0.1799	0.1312	0.1511	0.0635	0.1164	0.0677	0.0876
	8115.8120	0.2961	0.2214	0.2374	0.0989	0.1972	0.1225	0.1385
9	4051.7120	0.1659	0.1344	0.1125	0.0655	0.1004	0.0689	0.0470
	7021.4120	0.2525	0.1844	0.1829	0.0915	0.1609	0.0928	0.0914

Notched Racking Data								
Racked Across Length								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	1519.4680	0.1408	0.1003	0.1436	0.0804	0.1209	0.0804	0.1237
	2015.7480	0.1762	0.1238	0.1740	0.1023	0.1547	0.1023	0.1525
2	2005.1840	0.1425	0.1212	0.1395	0.0815	0.1028	0.0815	0.0998
	2774.0760	0.1853	0.1560	0.1702	0.1143	0.1436	0.1143	0.1285
3	2098.7400	0.1402	0.1275	0.0980	0.0821	0.0948	0.0821	0.0525
	4061.1360	0.2275	0.2053	0.1759	0.1423	0.1645	0.1423	0.1129
4	1503.8880	0.1314	0.0950	0.1246	0.0736	0.1100	0.0736	0.1032
	2062.8680	0.1582	0.1252	0.1575	0.0988	0.1318	0.0988	0.1311
5	2019.6240	0.1280	0.0934	0.1233	0.0756	0.1102	0.0756	0.1055
	3177.7120	0.1863	0.1450	0.1677	0.1127	0.1539	0.1127	0.1354
6	2006.6280	0.0958	0.0867	0.0929	0.0674	0.0765	0.0674	0.0735
	4044.2640	0.1712	0.1561	0.1618	0.1256	0.1406	0.1256	0.1313
7	1643.1200	0.1212	0.1184	0.1300	0.0759	0.0787	0.0759	0.0874
	1946.1320	0.1385	0.1318	0.1494	0.0910	0.0977	0.0910	0.1086
8	2011.4920	0.1195	0.1107	0.1250	0.0610	0.0698	0.0610	0.0752
	3041.2920	0.1672	0.1484	0.1674	0.0942	0.1131	0.0942	0.1133
9	2037.4840	0.0789	0.0770	0.0956	0.0505	0.0524	0.0505	0.0692
	4078.8440	0.1537	0.1237	0.1523	0.0973	0.1273	0.0973	0.1259

Racked Across Width								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	2608.5480	0.1591	0.2025	0.1493	0.1017	0.0583	0.1017	0.0485
	3290.3440	0.1979	0.2343	0.1837	0.1271	0.0907	0.1271	0.0765
2	2519.4000	0.1472	0.1848	0.1360	0.0690	0.0315	0.0690	0.0203
	3224.8320	0.1824	0.2174	0.1638	0.0907	0.0557	0.0907	0.0371
3	2755.3040	0.1820	0.1468	0.2505	0.0807	0.1159	0.0807	0.1844
	3885.9560	0.2343	0.1938	0.3032	0.1202	0.1607	0.1202	0.2295
4	2528.1400	0.1518	0.1757	0.1491	0.0897	0.0659	0.0897	0.0631
	3436.6440	0.1918	0.2196	0.1817	0.1231	0.0953	0.1231	0.0852
5	1518.0240	0.0964	0.0954	0.1284	0.0586	0.0595	0.0586	0.0915
	3084.8400	0.1600	0.1465	0.2148	0.1055	0.1189	0.1055	0.1737
6	1988.6920	0.1138	0.1053	0.1311	0.0755	0.0840	0.0755	0.1012
	3002.3040	0.1632	0.1416	0.1838	0.1108	0.1325	0.1108	0.1530
7	2500.0200	0.1483	0.1192	0.2231	0.0750	0.1040	0.0750	0.1789
	3552.6200	0.1911	0.1720	0.2628	0.1103	0.1295	0.1103	0.2011
8	2753.1760	0.1609	0.1753	0.1819	0.0757	0.0614	0.0757	0.0823
	3611.7480	0.2002	0.2145	0.2138	0.0985	0.0842	0.0985	0.0978
9	2545.8480	0.1208	0.1484	0.1144	0.0483	0.0207	0.0483	0.0143
	3513.9360	0.1516	0.1924	0.1464	0.0671	0.0263	0.0671	0.0211

Fork Tine Support **supports through notches** **string 3 next to LVDT**								
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**
1	3809.4240	0.1231	0.1418	0.1241	0.0689	0.0543	0.0730	0.0553
	6119.8240	0.1718	0.1932	0.1813	0.0990	0.0728	0.0942	0.0823
2	6228.8840	0.1998	0.1673	0.2619	0.0803	0.1195	0.0870	0.1816
	9148.1960	0.2626	0.2348	0.3297	0.1170	0.1455	0.1177	0.2126
3	7224.7120	0.1585	0.1553	0.1974	0.0884	0.0701	0.0669	0.1090
	9973.1000	0.2092	0.1993	0.2510	0.1201	0.0891	0.0792	0.1309
4	4320.9800	0.1674	0.1695	0.1588	0.0644	0.1031	0.1051	0.0944
	6102.9520	0.2053	0.2195	0.2035	0.0891	0.1161	0.1303	0.1143
5	5804.8800	0.2115	0.2522	0.1636	0.0790	0.1325	0.1731	0.0845
	7873.4480	0.2520	0.2978	0.2051	0.1033	0.1487	0.1945	0.1018
6	5318.5560	0.1354	0.133684	0.149112	0.07714	0.0583	0.0565	0.0720
	9350.5840	0.2032	0.199956	0.222452	0.121752	0.0815	0.0782	0.1007
7	3822.5720	0.2104	0.1522	0.2874	0.0642	0.1461	0.0879	0.2232
	5897.2200	0.2595	0.2003	0.3274	0.0890	0.1705	0.1114	0.2384
8	5642.1640	0.2092	0.1982	0.2273	0.0772	0.1321	0.1210	0.1501
	8066.1840	0.2576	0.2536	0.2752	0.1050	0.1526	0.1487	0.1702
9	5769.0080	0.1363	0.1520	0.1455	0.0761	0.0602	0.0759	0.0694
	8553.4200	0.1813	0.1903	0.1890	0.1047	0.0766	0.0856	0.0843

Table 3: Data table containing the light duty pallet bending test results.

(Blue=3 stringer, Green=4 stringer, Red=5 stringer)

Light Duty Non Notched Racking Data									
Racked Across Width									
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**	**Stiffness**
1	662.568	0.192584	0.189164	0.222832	0.157472	0.224276	0.220856	0.254524	4417
	1348.088	0.352792	0.325128	0.383952	0.298452	0.379468	0.351804	0.410628	
2	632.624	0.187264	0.178296	0.195852	0.15447	0.21109	0.202122	0.219678	5960
	1496.592	0.33554	0.327028	0.337592	0.306508	0.35606	0.347548	0.358112	
3	819.964	0.148352	0.15884	0.12692	0.142158	0.165034	0.175522	0.143602	7961
	1536.34	0.235828	0.241756	0.232712	0.222566	0.255018	0.260946	0.251902	
Fork Tine Support **supports through deckboards**									
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**	**Stiffness**
1	1192.82	0.07144	0.126768	0.087856	0.025384	0.046056	0.101384	0.062472	42850
	3553.836	0.163932	0.262048	0.205808	0.062776	0.101156	0.199272	0.143032	
2	1434.196	0.112632	0.061408	0.095	0.026486	0.086146	0.034922	0.068514	27786
	3885.956	0.230356	0.13566	0.159524	0.055974	0.174382	0.079686	0.10355	
3	1628.528	0.163704	0.052212	0.07334	0.018924	0.14478	0.033288	0.054416	18321
	4348.568	0.32794	0.101992	0.123728	0.034694	0.293246	0.067298	0.089034	
Top Deck Floor Stack **all stringers supported**									
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**	**Stiffness**
1	2452.9	0.075392	0.118864	0.071668	0.030058	0.045334	0.088806	0.04161	42452
	4558.1	0.134976	0.182476	0.11666	0.040052	0.094924	0.142424	0.076608	
2	7120.06	0.145008	0.119472	0.081852	0.045676	0.099332	0.073796	0.036176	153852
	11925.77	0.182932	0.153064	0.107388	0.052364	0.130568	0.1007	0.055024	
3	8184.136	0.13908	0.1273	0.093176	0.042446	0.096634	0.084854	0.05073	390192
	16368.8	0.171532	0.149188	0.12046	0.053922	0.11761	0.095266	0.066538	
Bottom Deck Floor Stack *all stringers supported**									
Pallet ID	Load	Pot 3	Pot 1	Pot 5	LVDT	**True Pot3**	**True Pot1**	**True Pot5**	**Stiffness**
1	1618.724	0.061864	0.100472	0.058672	0.02014	0.041724	0.080332	0.038532	43140
	2849.848	0.097888	0.15504	0.08322	0.027626	0.070262	0.127414	0.055594	
2	2573.36	0.045828	0.057304	0.047576	0.035416	0.010412	0.021888	0.01216	117879
	6215.128	0.087096	0.095912	0.07638	0.04579	0.041306	0.050122	0.03059	
3	6073.464	0.102904	0.073796	0.081016	0.041952	0.060952	0.031844	0.039064	231523
	11053.06	0.129352	0.089984	0.09728	0.046892	0.08246	0.043092	0.050388	

Table 4: Data Table containing joint rotation test results, MC, and SG

0.5" Joint Rotation							
Specimen	RM in-lbs/radian	MC %	SG	Specimen	RM in-lbs/radian	MC %	SG
D2	19858.28	8.74	0.50	S2	19858.28	13.5	0.5
D2A	7273.59	12.66	0.51	S2A	7273.59	18.9	0.4
D2B	14557.27	10.87	0.50	S2B	14557.27	15.4	0.4
D3	18971.56	8.79	0.42	S3	18971.56	18.4	0.5
D4	17856.52	8.97	0.49	S4	17856.52	15.2	0.5
D5A	15781.55	11.64	0.60	S5A	15781.55	14.5	0.4
D5B	9367.69	12.55	0.61	S5B	9367.69	18.6	0.4
D6	18038.31	8.69	0.51	S6	18038.31	12.7	0.5
D7	17040.70	10.24	0.53	S7	17040.70	13.5	0.5
D8A	7747.52	11.14	0.53	S8A	7747.52	9.7	0.4
D8B	8115.54	10.60	0.51	S8B	8115.54	13.3	0.4
D10A	7870.28	13.25	0.52	S10A	7870.28	17.9	0.4
D11B	5308.70	8.66	0.50	S11B	5308.70	9.7	0.4
Mean	12906.73	10.52	0.52	Mean	12906.73	14.7	0.4
StDev	5330.29	1.67	0.05	StDev	5330.29	3.1	0.0
COV	0.41	0.16	0.09	COV	0.41	0.2	0.0

1" Joint Rotation							
Specimen	RM in-lbs/radian	MC %	SG	Specimen	RM in-lbs/radian	MC %	SG
D13A	7153.26	12.44	0.48	S13A	7153.26	9.19	0.37
D13B	4462.05	12.25	0.46	S13B	4462.05	14.31	0.42
D17A	6342.86	11.20	0.44	S17A	6342.86	11.42	0.37
D17B	6764.20	10.14	0.44	S17B	6764.20	10.77	0.37
D30A	8064.14	11.01	0.43	S30A	8064.14	9.49	0.35
D30B	5365.55	9.22	0.44	S30B	5365.55	9.47	0.39
D47A	4805.27	11.89	0.40	S47A	4805.27	14.17	0.41
D47B	7797.07	13.58	0.43	S47B	7797.07	15.41	0.38
D48A	7547.02	12.25	0.40	S48A	7547.02	11.63	0.41
D48B	8302.13	9.80	0.43	S48B	8302.13	15.27	0.42
D58B	6213.26	10.51	0.45	S58B	6213.26	10.04	0.36
D61A	8280.03	13.14	0.49	S61A	8280.03	13.84	0.41
Mean	6758.07	11.45	0.44	Mean	6758.07	12.08	0.39
StDev	1340.22	1.36	0.03	StDev	1340.22	2.38	0.02
COV	0.20	0.12	0.06	COV	0.20	0.20	0.06

Table 5: Data table containing joint nail withdrawal test results

Half Inch Deck Board Nail Withdrawal							
Specimen	P1 (lbs.)	Δ1 (in.)	P2 (lbs.)	Δ2 (in.)	P2-P1 (lbs.)	Δ2-Δ1 (in.)	Stiffness (PSI)
h1	26.07	0.000	93.57	0.002	67.5	0.00154	43831.17
h2	34.83	0.000	104.78	0.002	69.95	0.00127	55078.74
h3	32.68	0.000	117.88	0.002	85.2	0.00206	41359.22
h4	14.27	0.000	101.98	0.002	87.71	0.0017	51594.12
h5	12.52	0.000	109.14	0.003	96.62	0.00312	30967.95
h6	21.36	0.000	112.04	0.002	90.68	0.00186	48752.69
h7	14.67	0.000	115.56	0.002	100.89	0.00151	66814.57
h8	25.02	0.000	106.16	0.003	81.14	0.00231	35125.54
h9	24.69	0.000	153.76	0.004	129.07	0.00373	34603.22
h10	20.13	0.000	135.36	0.004	115.23	0.00334	34500.00
h11	27.1	0.000	103.13	0.002	76.03	0.00145	52434.48
h12	30.73	0.001	187.63	0.005	156.9	0.00475	33031.58
						Mean	44007.77
						StDev	11074.50
						COV	0.25

One Inch Deck Board Nail Withdrawal							
Specimen	P1 (lbs.)	Δ1 (in.)	P2 (lbs.)	Δ2 (in.)	P2-P1 (lbs.)	Δ2-Δ1 (in.)	Stiffness (PSI)
o1	49.56	0.000	123.08	0.002	73.52	0.00137	53664.23
o2	28.13	0.000	102.95	0.001	74.82	0.00111	67405.41
o3	24.05	0.000	107.63	0.001	83.58	0.00091	**91846.15**
o4	44.47	0.000	117.74	0.002	73.27	0.00129	56798.45
o5	17.96	0.000	105.33	0.002	87.37	0.00195	44805.13
o6	53.09	0.000	152.09	0.001	99	0.00116	**85344.83**
o7	22.49	0.000	87.1	0.001	64.61	0.0012	53841.67
o8	8.09	0.000	52.7	0.002	44.61	0.00219	20369.86
o9	13.07	0.000	94.45	0.002	81.38	0.00174	46770.11
o10	41.58	0.000	144.57	0.002	102.99	0.00186	55370.97
o11	42.31	0.000	120.01	0.002	77.7	0.00201	38656.72
o12	52.51	0.000	127.56	0.001	75.05	0.00095	**79000.00**
						Mean	57822.79
						StDev	20354.22
						COV	0.35

Table 6: Data table containing MC and SG of joint nial withdrawal specimens.

Half Inch and One Inch Deck Boards and Stringers					
Specimen	Wet Wt (g))	Dry Wt (g)	Vol Disp (cm³)	MC (%)	SG
h1	6.46	6.03	12.85	5.46	0.47
h2	5.8	5.43	11.96	4.8	0.45
h3	7.66	7.14	14.42	6.66	0.50
h4	6.38	5.95	11.42	5.38	0.52
h5	7.49	7.01	14.82	6.49	0.47
h6	6.96	6.49	13.27	5.96	0.49
h7	7.25	6.77	15.33	6.25	0.44
h8	6.59	6.17	13.98	5.59	0.44
h9	8.27	7.73	14.55	7.27	0.53
h10	6.59	6.15	14.8	5.59	0.42
h11	8.03	7.49	15.64	7.03	0.48
h12	6.34	5.93	14.68	5.34	0.40
h1	9.97	9.28	21.74	8.97	0.43
h2	11.02	10.26	24.6	10.02	0.42
h3	11.77	10.95	26.09	10.77	0.42
h4	11.1	10.36	24.09	10.1	0.43
h5	9.53	8.84	21.69	8.53	0.41
h6	9.33	8.67	20.87	8.33	0.42
h7	11.54	10.77	25.85	10.54	0.42
h8	8.94	8.32	21.14	7.94	0.39
h9	9.19	8.53	20.34	8.19	0.42
h10	9.68	9.06	22.69	8.68	0.40
h11	12.54	11.7	26.19	11.54	0.45
h12	8.77	8.17	19.75	7.77	0.41
			Mean	7.63	0.44
			St Dev	1.97	0.04
			COV	0.26	0.09
Specimen	Wet Wt (g)	Dry Wt (g)	Vol Disp (cm³)	MC (%)	SG
o1	11.45	10.66	23.2	10.45	0.46
o2	13.43	12.46	26.53	12.43	0.47
o3	12.76	11.92	28.02	11.76	0.43
o4	14.14	13.21	27.57	13.14	0.48
o5	10.33	9.65	20.69	9.33	0.47
o6	13.18	12.22	24.69	12.18	0.49
o7	11.67	10.92	24.36	10.67	0.45
o8	10.93	10.26	22.52	9.93	0.46
o9	10.33	9.69	20.82	9.33	0.47
o10	10.2	9.6	22.88	9.2	0.42
o11	8.17	7.65	19.42	7.17	0.39
o12	13.74	12.91	26.51	12.74	0.49
o1	12.78	11.94	28.72	11.78	0.42
o2	11.92	11.18	26.57	10.92	0.42
o3	10.74	10.03	24.38	9.74	0.41

o4	10.64	9.93	24.09	9.64	0.41
o5	11.75	11	25.59	10.75	0.43
o6	13.72	12.82	31.52	12.72	0.41
o7	10.48	9.8	24.8	9.48	0.40
o8	12.75	11.9	28.22	11.75	0.42
o9	13.76	12.85	29.47	12.76	0.44
o10	12.44	11.66	28.46	11.44	0.41
o11	10.87	10.2	25.44	9.87	0.40
o12	12.94	12.13	30.03	11.94	0.40
			Mean	10.88	0.43
			St Dev	1.50	0.03
			COV	0.14	0.07

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