EVALUATION OF METAL CONNECTOR PLATES FOR REPAIR AND REINFORCEMENT OF WOOD PALLETS

by

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(ABSTRACT)

Pallet repair and reinforcement with metal connector plates (MCPs) may reduce wood waste while providing pallet users with quality, economical pallets. The study objectives were to evaluate the effect of MCP repair and reinforcement on pallet performance, and to evaluate preliminary standards for repair and reinforcement of pallets with MCPs. Whole pallets and pallet components were tested. Stringers and notched segments were tested in static bending, while end feet were tested for resistance to fork tine impact. Whole pallets were evaluated with a test protocol that simulated the effects of long-term handling. Stringers, repaired at notch corners, had greater strength, but less stiffness than the original stringers. Notch reinforcement with MCPs resulted in stringers with greater strength and stiffness than equivalent unreinforced stringers. No consistent species-width effect was found for strength of plated stringers. MCP-repair of above-notch failures did not restore the original strength or stiffness of notched segments. However, these repairs may be satisfactory since above-notch failures are secondary in frequency of occurrence. No differences were found between performance of plates used to repair stringers and notched segments. Both repaired and reinforced

end feet had greater impact resistance than the equivalent original or unreinforced end feet. Wood species, rather than stringer width, had a greater influence on MCP performance. In general, tests of whole pallets supported the results from component tests which suggests that component testing may be a practical means of assessing the effect of repair and reinforcement techniques on pallet performance.

ACKNOWLEDGEMENTS

I would like to acknowledge the advice and guidance of committee chairman Dr. T.E. McLain, whose patience and support made this project enjoyable. I also appreciate the many suggestions from the other members of my committee, Dr. M.S. White, Dr. J.R. Loferski, and Philip Araman. I also appreciate the assistance of the Brooks lab staff, J.W. Akers, Kenny Albert, Charlotte Barnett, Carlile Price, Harrison Sizemore, and Harold Vandivort.

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This project would not have been possible without the support and assistance of many pallet and metal plate manufacturers, including Abell Industries, Alpine Engineered Products, Inc., Brunswick Box Company, Inc., Eagle Metal Products, Mitek Industries, Inc., Pallet Repair Systems, Pallet Repairs of NC, Inc., Potomac Supply Corporation, Senco Products, Inc., Williamsburg Millwork Corporation, and Woodthorn Corporation.

I would like to thank my parents and family for encouraging me to pursue this degree. And finally, I would like to thank my wife, Tiffany, for her patience and understanding with me and our son, Will, throughout this project.

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1.0 INTRODUCTION

1.1 OVERVIEW

Pallets, introduced in the 1930's, are the preferred method of shipping and handling many types of goods, providing a convenient way to transport unit loads with a forklift. Pallets are manufactured from various materials, including wood, steel, aluminum, high density polyethylene (HDPE) and corrugated fiberboard or honeycomb [1]. Although there is increasing competition, wood remains the most common pallet material, with over 536 million wood pallets manufactured in the US in 1990 [2].

Industry estimates show that, in 1990, 57% of the wooden pallets produced were expendable or one-way pallets [2]. As timber prices and landfill disposal costs increase, however, the expendable pallet will become more expensive to the user and ultimately the consumer. Higher costs may make pallets from alternative materials more attractive. Stronger, reusable pallets that can withstand multiple handlings may sometimes be more economical over the life of the pallet than expendable pallets. Repair and reinforcement are two methods of getting more use from wooden pallets. The purpose of pallet repair is to convert a damaged pallet to a functional one for a minimal cost, thus extending its economic life. Pallet reinforcement has the potential to increase the strength properties of an undamaged pallet, reduce potential damage, and also increase total economic life.

Repair methods and the extent of repair can affect the quality of the pallet. This study focuses only on stringers and stringer-class pallets, since it is generally more economical to replace deckboards than to replace stringers, and no MCPs are currently manufactured for deckboard repair. The National Wooden Pallet and Container

Association (NWPCA) maintains the Logo-Mark Pallet Repair Standards [3], which outline methods and levels of repair. These standards require the use of additional wooden members to complete repairs.

Wood pallet stringers commonly fail between the notches (BN), above the notches (AN), and in the end foot (see Figure 1.1). The first two result from bending loads on a notched beam, while the third is usually the result of an impact from a forklift tine. Metal connector plates (MCPs or plates) applied to repair fractures in these areas could return a damaged pallet to its original strength or stiffness. Alternatively, MCPs applied to reinforce these areas before use could increase economic life and load carrying capacity, as well as allowing for the potential use of underutilized species.

Recently, interest in the use of MCPs for stringer repair and reinforcement has increased. MCPs have potential for an effective repair with minimum cost and maximum benefit. Concern has been expressed, however, over the minimum quality standards for MCPs and repair procedures. Inadequate standards will result in reduced consumer acceptance of pallet repair and wooden pallets, in general.

The NWPCA, recognizing the importance of MCPs for pallets, has expressed interest in developing a product performance standard as a basis for promoting pallet metal plate repair and reinforcement. The NWPCA has issued Interim Guidelines for the Use of Pallet Metal Connector Plates [see Appendix A]. The development of a comprehensive standard requires a better understanding of the effects that plate design, application procedures, and other factors have on the performance of new and repaired pallets. In addition, standard test procedures and performance criteria are needed. The global objective of this thesis is to provide technical support to this development issue.

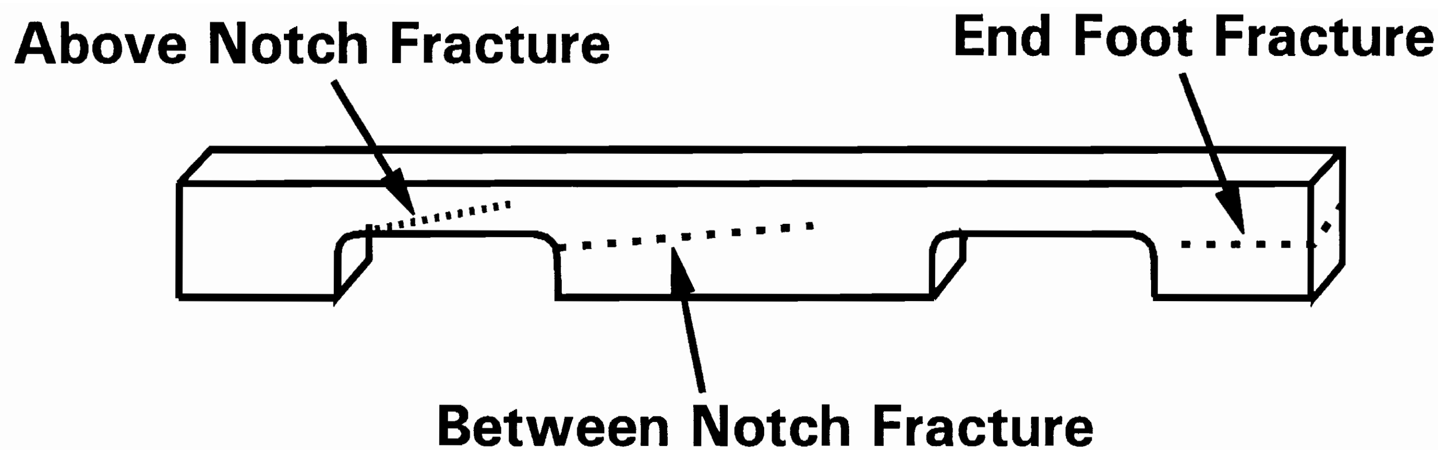

Figure 1.1 Schematic diagram of a notched stringer showing the three damages to be repaired and evaluated.

1.2 RESEARCH OBJECTIVES

The overall objectives of this research were to:

a) Evaluate the effect on pallet performance of repair and reinforcement of stringers with metal connector plates, and

b) Evaluate existing performance standards for repairing and reinforcing stringer-class pallets with metal connector plates.

Specific sub-objectives to:

a) Evaluate any effect of plate design, mechanical fracture closing, fracture length, species, and width on the bending performance of repaired stringers.

b) Evaluate any effect of plate design, fracture length, species, and width on the bending performance of repaired stringer notch segments.

c) Evaluate any effect of plate design, fracture type, species, and width on the impact resistance of repaired end feet.

d) Evaluate any effect of species, width, and species substitution on the bending performance and end foot impact resistance of reinforced stringers.

f) Evaluate any effect of repair and reinforcement methods on the bending performance of stringer-class pallets made of three different species.

g) Develop test methods for determining some performance characteristics of repaired and reinforced stringer components.

2.0 LITERATURE REVIEW

2.1 PALLET DURABILITY AND DESIGN

Pallets are made to transport a wide variety of goods, hence, they come in many sizes and configurations. Most designs are variations of either block-class or stringer-class pallets. That is, one or two faces of deckboards are connected to either stringers or blocks. Only stringer-class pallets are considered in this study as, at this time, they represent 83%-86% of the US pallet production [2].

The NWPCA Logo-Mark Pallet Repair Standards [3] classify pallet repairs according to the damaged part and the replacement parts. An R-1 repair permits the replacement of only damaged deckboards. Grade R-2 and R-3 repairs permit the repair of stringers as well as deckboards. The R-2 repair standards require a full companion stringer to be nailed adjacent to the damaged stringer, while the R-3 repair standards require only a half-stringer to provide the strengthening function. R-1 and R-2 repair standards are designed to bring the strength of a damaged pallet to that of a new, undamaged pallet. Pallets meeting R-3 criteria will have a lower capacity.

The NWPCA also classifies the lumber species used in pallets, according to density [6]. Class C contains the densest species, Class B the intermediate species, and Class A the least dense species. Of the species tested in this research, yellow poplar and southern yellow pine are Class B species, and oak is a Class C species.

There are many physical failure modes found with stringer-class pallets. However, the predominant failures in notched stringers may be grouped into three categories resulting from two types of loading (see Figure 1.1). End foot failures usually result from an impact load by a forklift tine to the end of a stringer. Between notch (BN) failures and above notch (AN) failures generally result from bending loads applied when the loaded pallet is stored or transported. Deckboard and deck-stringer connection failures are not considered in this study.

Notching stringers permits partial four-way entry to a pallet for forklifts, and is specified by many pallet users. But notches create stress-risers in the stringer and as a result, most pallet stringers needing repair have failed at this notch, or, at least, cracks have formed at the notch root. Failure of a notched wood beam is governed by a combination of tensile stresses perpendicular to the grain and shear stresses parallel to grain [7]. Previous researchers [8,9] have developed means to predict the breaking strength of notched pallet stringers. Generally, the strength of the notch will govern the strength of the pallet. These methods do not apply after the notch crack has propagated.

The Pallet Design System, PDS [1], is a reliability-based engineering design software program for wooden pallets. Users can input pallet variables to "build" a pallet in the computer. The system provides a method to balance functionality with economy. A properly designed pallet will lower product damage rates, repacking costs, and insurance costs, and improve the handling rates and efficiency of pallet users. PDS, however, is not applicable to repaired pallets.

2.2 METAL CONNECTOR PLATES

Metal connector plates (MCPs or plates) consist of a flat piece of sheet steel with punched teeth. The teeth are integral metal projections of the plate formed perpendicular to the plate during the stamping process [10]. These teeth enable the plate to grip wood when pressed into the fiber, and they are designed to transmit lateral loads. MCPs are manufactured from ASTM A446, A591, A792, or A167 structural quality steel protected with zinc or zinc-aluminum alloy coatings or its stainless steel equivalent.

MCPs are manufactured to various sizes and thicknesses (see Table 3.1 and Figures 3.1-3.12 for examples of pallet plates). Their use is historically associated with light-frame wood truss systems. MCPs made possible the prefabrication of roof and floor trusses where the members are joined together with plates. With MCPs, wooden members may be joined to create systems which can span distances longer than any of the individual members.

Factors affecting the performance of MCPs, neglecting the effects of the teeth and lumber, are: length, width, thickness of plate; location, spacing, orientation, size, and shape of holes in the plate; stress concentrations around projections and perforations of the plate; and basic properties of the plate metal [10].

During manufacture and subsequent in-use loading of plates, stress concentrations develop around holes, teeth, plugs, etc. Because of these stress concentrations and the difficulty of predicting the path of failure, design values for plates must be based on tests rather than analytical methods [11]. These tests have typically been uniaxial tension or compression and shear.

Truss connections are rarely assumed to carry moment and there are no standardized tests to provide guidelines for testing the moment capacities of MCP connections. Wolfe [12] evaluated the load capacity of metal plate connections under bending loads, axial tension loads, and combinations of both axial tension and bending loads. For pure axial tension tests, 40% of the test MCP connections failed due to yielding of the steel in the MCP, and the rest failed due to plate tooth withdrawal. For pure bending tests, all specimens failed due to MCP steel yielding. The compression edge of the MCP buckled and the tension edge was strained to failure. Combined bending and tension tests also resulted in all steel yielding failures. Wolfe also found that combined loading of connections resulted in significant decreases in axial capacity as the bending moment increased, and that metal plate connections subjected to combined bending and axial tension should be checked for their interactive load capacity. A repaired stringer in racked-across stringer (RAS) applications, where the MCP is essentially holding two members (each side of the fracture) together, is subject to bending moment, although the predominant plate stresses are tension perpendicular to grain and shear.

Standardized tests by the Truss Plate Institute (TPI) have been established to evaluate MCPs in tension and shear [10,11,13]. These tests, however, do not directly simulate loads on MCPs applied to pallet stringers.

2.3 PALLETS AND METAL CONNECTOR PLATES

Metal connector plates are not entirely new to pallets. In the early 70's, Automated Building Components, Inc. developed guidelines for repairing pallet deckboards and reinforcing pallet stringers with "Gang-Nail" connectors [14]. Stern [15] used double, 20-gauge metal connector plates to reinforce aspen stringer-to-deckboard joints. Impact torsional and shear tests indicated that the ultimate torsional and shear resistance, torsional rigidity, and shear stiffness of the MCP reinforced joints could be increased, on average, to 1½ times that of unreinforced joints.

However, pallets have traditionally been viewed as disposable, low-cost units manufactured of inexpensive low-grade materials, and not worth the extra trouble of plating for longer use. Pallet stringer repair is traditionally a companion stringer nailed next to the broken stringer. This is a labor-intensive process which also reduces the effective opening for fork entry, raising the potential for future damage. Most pallets are considered expendable and are discarded after first use or failure. Today, however, wood raw materials are increasing in cost, and society has greater concern about waste and recycling. MCPs may now be more promising and offer the advantage of a quick, effective method to strengthen a pallet for a minimal cost. The disadvantages are the cost of plates and an MCP pressing machine (instead of a hammer or nail gun). The lack of uniformly accepted MCP repair standards (other than interim standards) hinders the acceptance of MCP repair in the marketplace.

MCPs for pallets are applied with mechanical presses made by several manufacturers. The plates are applied with a hydraulic press, with various proprietary fixture configurations. Many machines also mechanically close fractures before MCP application.

Testing of MCPs for pallet repair and reinforcement is necessary since, unlike trusses, there are no reasonable analytical methods to predict repaired or reinforced stringer strength. Due to potential misuse of MCPs for repair pallets, the NWPCA has issued voluntary-use guidelines [4]. These guidelines were developed as an interim measure to provide an industry baseline until the completion of this research.

Some recent testing with MCPs and pallets by proprietary sources indicates varied results. Rainier Pallet Corporation [16] tested five, 48"x40", 4-way hardwood grocery pallets repaired with Clary 3"x4" pallet plates (see Table 3.1 and Figure 3.2). Each pallet was loaded with a 4000 pound block and supported in RAS mode for one week. In cases where a pallet did fail, a previously unbroken and unplated stringer was the cause of failure.

Mitek of South Africa [17] tested stringers in third-point static bending, as specified in ASTM D198 [18]. Several different sizes of TECO GN20 plates (no description given) were used for repair, depending on the type and severity of fracture. All stringers were then retested in static bending. They found that TECO GN20 nail plates did restore broken stringer strength to the lower 5th percentile of original stringers, but that repaired stringer stiffness was 35% less than for original stringers.

Clary Corporation [19] conducted an evaluation of its 3"x4" between notch pallet plate (see Table 3.1 and Figure 3.2). All three stringers of a "Grade A" pallet were intentionally broken. Stringers were repaired with a scissor-jaw type hydraulic press and Clary pallet plates. The repaired pallet was loaded to 5100 pounds and, after 30 minutes, the average midspan deflection was 1/8th inch. This deflection was very similar to that for unbroken, unrepaired pallet stringers under the same loading conditions. This test included only one repaired pallet, and no mention was made of species.

Clary 3"x4" pallet plates were also used to join various pieces of hardwood pallet materials. Plates were centered about the splice points. The samples were pulled in tension until ultimate failure was reached. The average load for the ten spliced samples was 6666 lbs. Plate tooth withdrawal resulted in 85% of the failures, and metal failure the remaining 15%.

Alpine Engineered Products, Inc., [20] conducted static bending tests on 60 stringers and 5 full pallets. The samples were tested to failure in static bending to determine the original strength. Most fractures were then repaired with 2¾"x3" WOODLOC brand plates. Two of the pallets failed above stringer notches and were repaired with 2"x5½" WOODLOC plates (see Table 3.1 and Figures 3.1,3.7). The samples were then retested in static bending to determine the repaired strength. The repaired strength was greater than that of the original strength for 87% of the stringers and 100% of the pallets. The repaired stringers that were not as strong as the originals (13%) failed at notches away from the MCP repair, suggesting repair of all between notch areas, not just the ones at which failure occurred, would increase repaired stringer strength.

The Chisholm Institute of Technology [21] conducted impact testing of stringer end feet reinforced with end grain MCPs. Plates were PPC brand, 1¾"x3½" (1.2mm thick), with truss-type teeth. One end foot of a stringer was reinforced with the MCP, while the opposite end foot remained unplated. Stringers were then sawed in half to obtain closely matched samples. The impact machine was pendulum-type, with a one ton mass and simulated forklift tine.

Velocity of the pendulum at impact in the range of 0-5 km/hr was estimated as a function of the height through which the pendulum dropped. There was no instrumented measurement of true velocity. Kinetic energy (E_f) was taken as proportional to the square of the computed velocity ($E_f = \frac{1}{2}mv^2$). Tests found that the velocity of the pendulum needed to split the foot in one impact was 2 km/hr for the unplated samples and 3 km/hr for the plated samples. The resulting crack lengths were similar for both plated and unplated samples, that is, plated end feet eventually failed in a manner similar to that of unplated end feet. The test velocities required to cause failure corresponded to a 125% greater energy adsorption of the plated samples over the unplated samples.

Later, Douglas-Fir sample groups were tested normal to, at an angle to the end grain surface, and on the side of the stringer with the same test machine. Five types of end grain MCPs were used for reinforcement, and one group of samples was tested unreinforced. Test results showed MCPs reinforcing the end grain of stringers increased by several times their resistance to splitting as compared to unreinforced stringers. The best performing plate was the Claw 3 Long Tooth, which had a longer tooth designed especially for softwoods. In normal impacts to the end grain surface, 1.0 mm thick plates increased resistance to splitting by 4.9 times over unreinforced resistance, while 1.2 mm thick plates increased resistance to splitting by 5.9 times over unreinforced resistance. Angle blows to the end gave similar results, and angle blows to the sides of the reinforced stringers caused no splits.

2.4 METHODS OF TESTING

2.4.1 Static Bending Tests

Standard test methods for static bending of pallets and stringers are prescribed by the American Society for Testing and Materials (ASTM). Testing for pallets is covered in ASTM D1185-85 [22] "Standard Test Methods for Pallets and Related Structures Employed in Materials Handling and Shipping." Testing of full stringers, as lumber, is covered in ASTM D198-84 [18] "Standard Methods of Static Tests of Timbers in Structural Sizes." No standard currently exists for testing segments from the above notch area of stringers.

2.4.2 Dynamic Impact Tests

Pallets are also subject to shock or impact loads when dropped, shaken, and hit by other objects. Tests to simulate these loads have been standardized in various ASTM tests. ASTM D1185 [22] outlines procedures for testing pallets with forklift tine impacts. The loaded pallet is placed on an inclined test carriage and impacts a simulated forklift tine. The results are only visual, such as a broken stringer or loose deckboard joint. No method of obtaining quantifiable results are detailed. ISO 8611 [23], TR 20232 [24], and TR 20233 [25] outline test methods for static and impact tests of block pallets, but do not currently address stringer pallets. No standard test currently exists that simulates forklift tine impacts to an end foot segment.

3.0 METHODS AND MATERIALS

3.1 OVERVIEW

Research on wooden stringers and pallets with metal connector plates (MCPs) was conducted in two integrated phases. The first focused on repair and the second focused on reinforcement. For both phases, tests were conducted to assess:

(a) the flexural strength and stiffness of repaired or reinforced stringers, and

(b) the impact resistance of repaired or reinforced stringer end feet.

Part (a) was determined by static bending tests of full stringers and notched stringer segments, and part (b) by dynamic shear/cleavage impact tests of stringer end feet.

It was expected that the performance of repaired and reinforced stringers would approximate the performance of repaired and reinforced pallets in actual use. To confirm this hypothesis, accelerated field testing of repaired and reinforced pallets was conducted. The results of these pallet tests provided comparative damage severity data and insured that the bending and impact tests of pallet components adequately characterized full pallet damage.

Some common terms and their meanings in this thesis are given below. These definitions apply unless otherwise stated.

Stringer - A notched pallet stringer, 48 inches in length, with actual cross-section dimensions of either 1½" x 3½" or 2½" x 3½". Two notches, located 6" from each end, 1½" deep, and 9" long with a ½" fillet radius were used. This is a common notched stringer geometry.

Notched Stringer Segment - The notch area of a stringer used for testing. The segment, 14 inches long, had actual cross-section dimensions of either 1½" x 3½" or 2½" x 3½". The 9 inch long notch, described above, was centered in the 14" length.

End Foot - The end foot area of a stringer used for testing. The end foot specimen was 12 inches long with actual cross-section dimensions of either 1½" x 3½" or 2½"x 3½". The samples contained approximately 6" of actual end foot, with the notch described above for stringers located along the remainder of the sample.

Pallet - The test pallets were flush, non-reversible, partial 4-way, 48x40 stringer-style with the following specifications:

Stringers - 3 pcs., 1½" x 3½" x 48"

Top Deck - 2 pcs., ⅝" x 6" x 40"; 5 pcs., ⅝" x 4" x 40"

Bottom Deck - 2 pcs., ⅝" x 6" x 40"; 3 pcs., ⅝" x 4" x 40"

Species - The species groups used were mixed eastern oaks (*Quercus* spp.), southern yellow pine (*Pinus* spp.), and yellow poplar (*Liriodendron tulipifera*). Not all species were used in all areas of testing.

Grade - Full stringer quality conformed to PDS Grade 3 [1]. This is equivalent to NWPCA Grade 4 or better [26]. Notched stringer segments and end feet conformed to the applicable parts of these grade rules.

Moisture Content - Two moisture content (MC) levels were recognized, green and dry. Green referred to the MC of samples when procured from the pallet manufacturers.

Dry referred to the MC of samples at or below 12% MC. To ensure equal moisture contents at testing, all specimens were dried to approximately 12% MC, then placed in an environmental chamber to equilibrate at 20°C and 65% relative humidity for one week. These conditions are equivalent to approximately 12% equilibrium moisture content.

3.2 METAL CONNECTOR PLATES

All known manufacturers of pallet metal connector plates (MCPs or plates) were asked to contribute MCP samples. From these samples, thirteen test MCPs were selected to represent the various designs and manufacturers.

Table 3.1 and Figures 3.1-3.12 describe and illustrate the metal connector plates. All plates used for testing were assigned a generic name. MCPs for the repair or reinforcement of between notch failures were assigned the letters "BN", MCPs for above notch failures were assigned "AN", and end-grain MCPs for end feet were assigned "EG". All plates evaluated were 20 gauge thickness (0.034 inch). All plate teeth were ⅓ inch in length except EG2, which had teeth ½ inch in length.

3.3 COMPONENTS AND ASSEMBLY

MCPs were evaluated using three wood species and two stringer widths. The species were mixed eastern oaks (oak), southern yellow pine (SYP), and yellow poplar (YP). The stringer widths were 1½ inches and 2½ inches.

TABLE 3.1: Description of Metal Connector Plates			
Type[1]	Size (in.)	Tooth style	Figure
BN1	3x3	round, 6-tooth plug	3.1
BN2	3x4	round, 4-tooth plug	3.2
BN3	3&2x6[2]	truss type, 2-tooth, in-series	3.3
BN4	3x4	X-shaped, 4-tooth plug	3.4
BN5	3x4	truss type, 2-tooth, alternating	3.5
BN6	3x4	round, 5-tooth plug	3.6
AN1	2x6	truss type, 2-tooth, alternating	3.7
AN2	2x6	round, 4-tooth plug	3.8
AN3	3&2x13[2]	truss type, 2-tooth, in-series	3.9
AN4	2x6	X-shaped, 4-tooth plug	3.10
AN5	2x6	round, 5-tooth plug	3.11
EG1	1.25x3.25	truss type, 2-tooth, alternating	3.12
EG2	1.25x3.25	truss type, 2-tooth, alternating	3.12

[1] Plate names indicate use: BN = between the notches, AN = above the notches, EG = end grain.

[2] Plate shape conforms to stringer notch, see Figures 3.3,3.9.

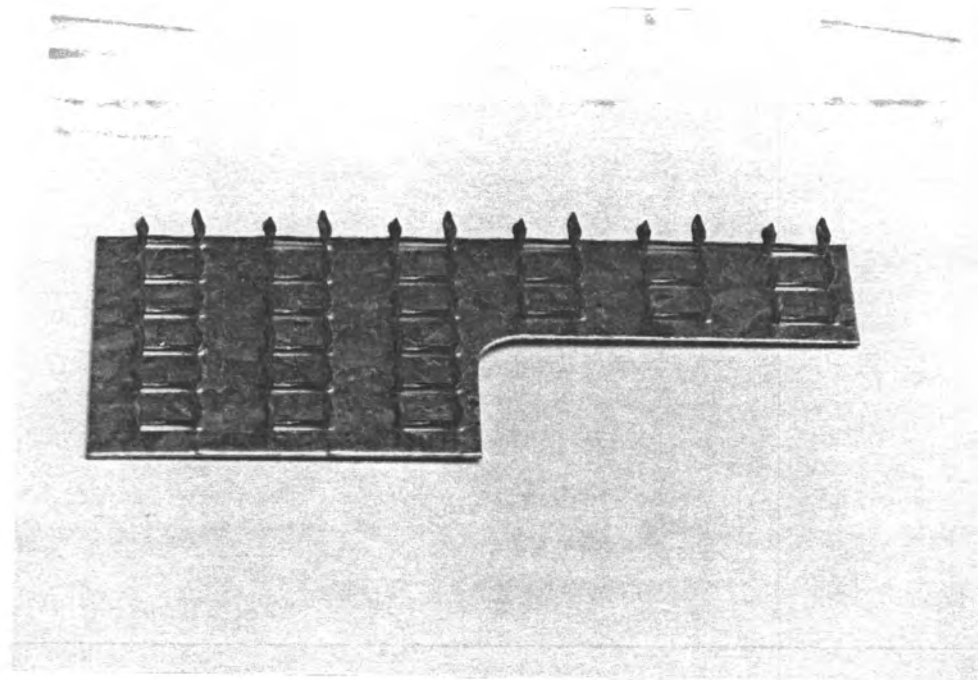

Figure 3.3. Plate BN3

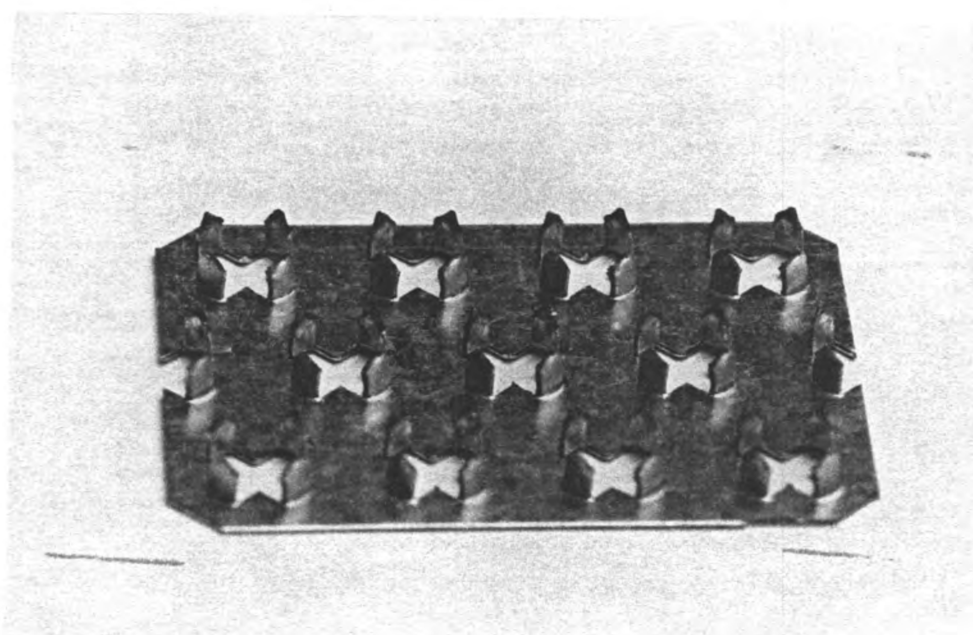

Figure 3.4. Plate BN4

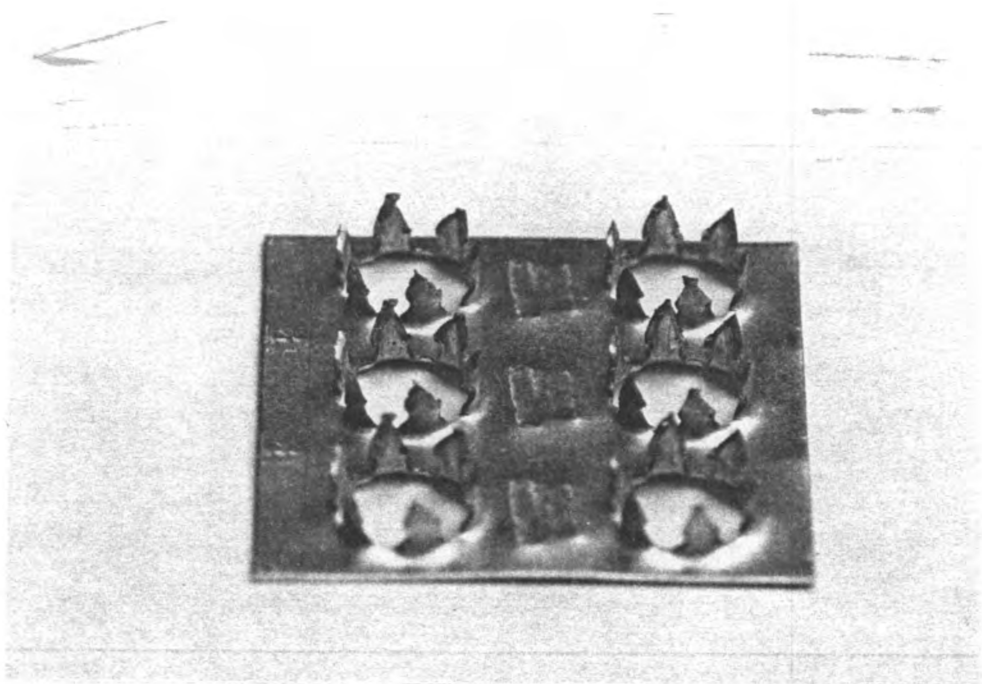

Figure 3.1. Plate BN1

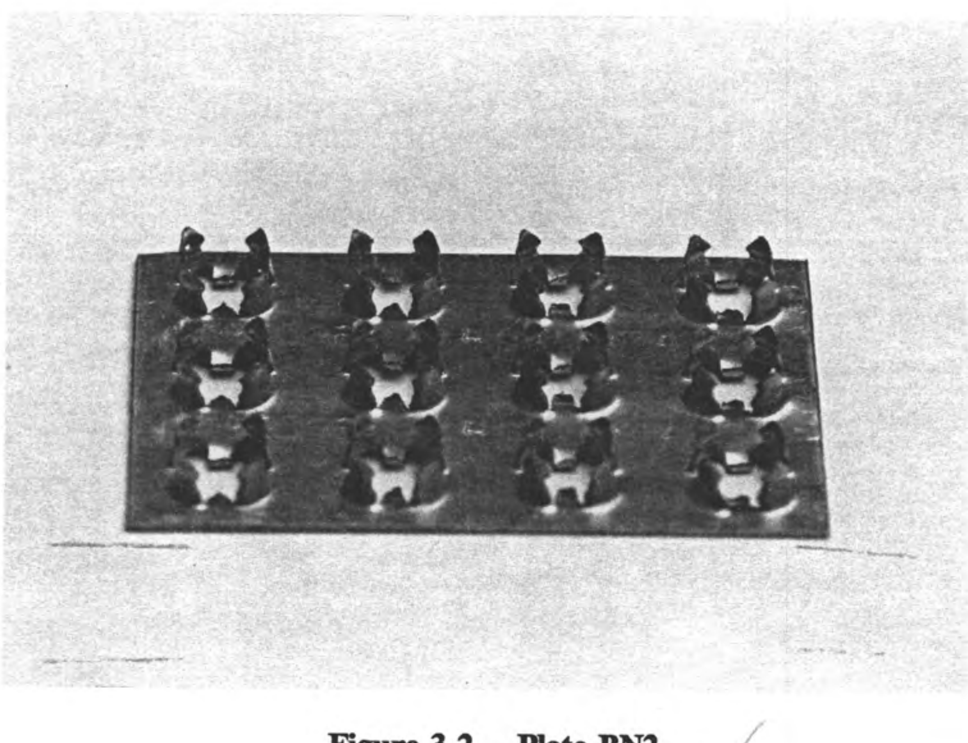

Figure 3.2. Plate BN2

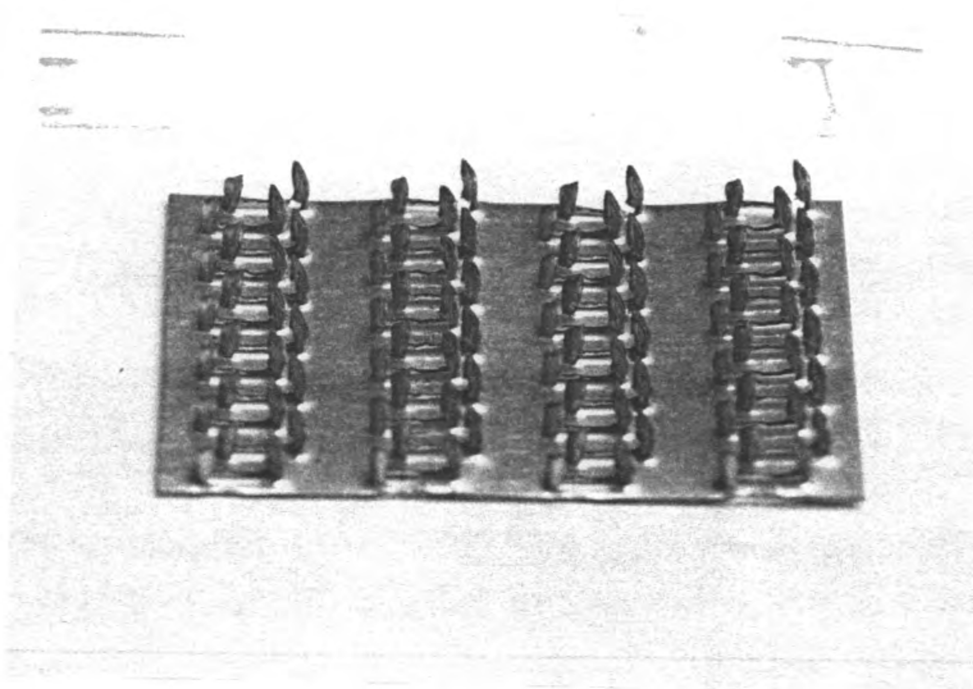

Figure 3.5. Plate BN5

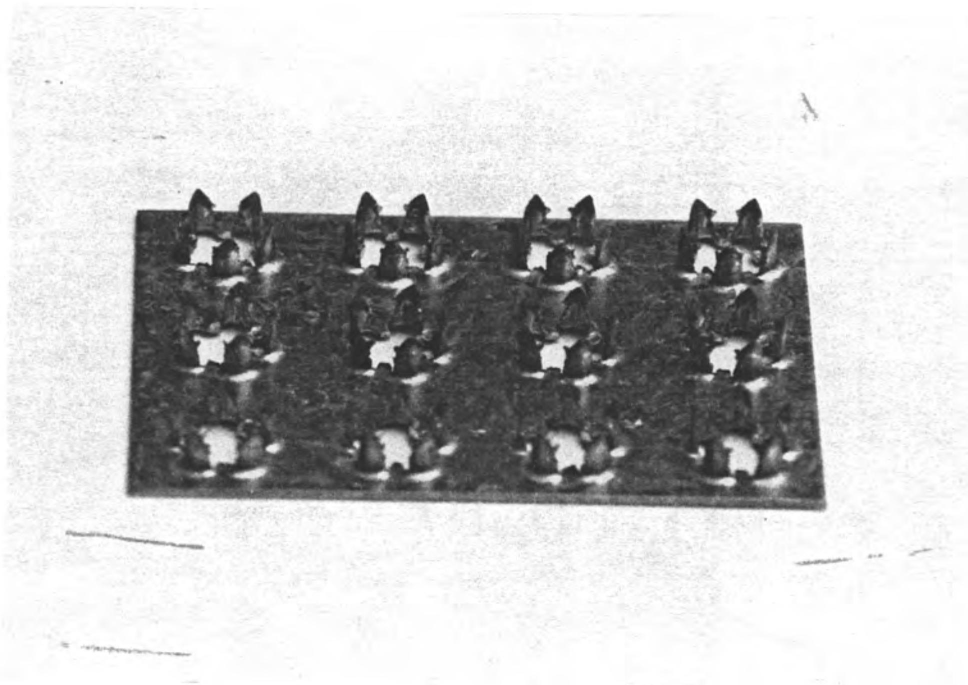

Figure 3.6. Plate BN6

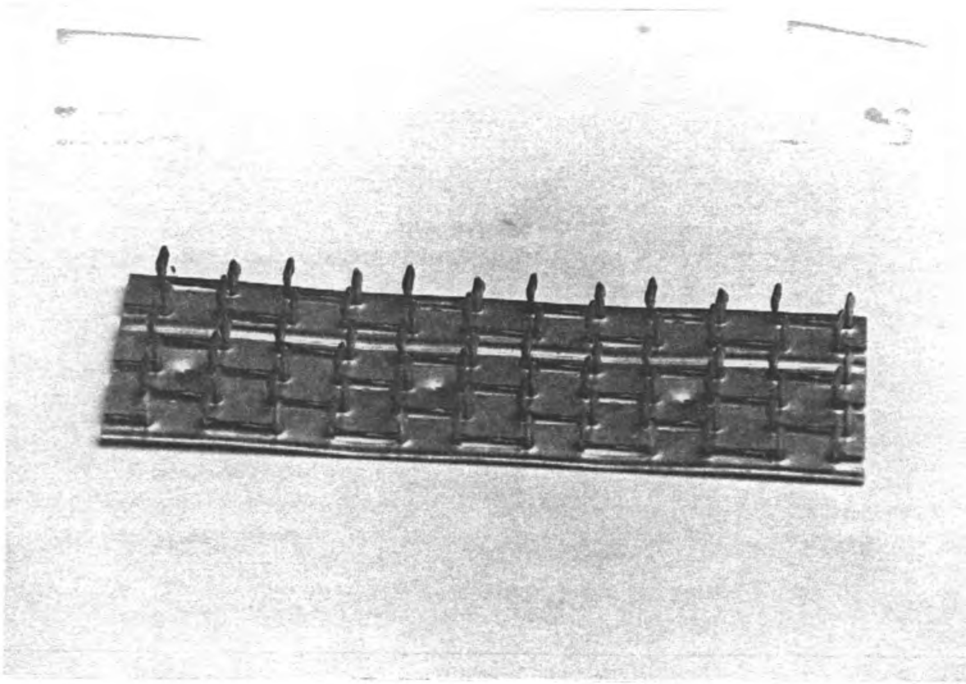

Figure 3.7. Plate AN1

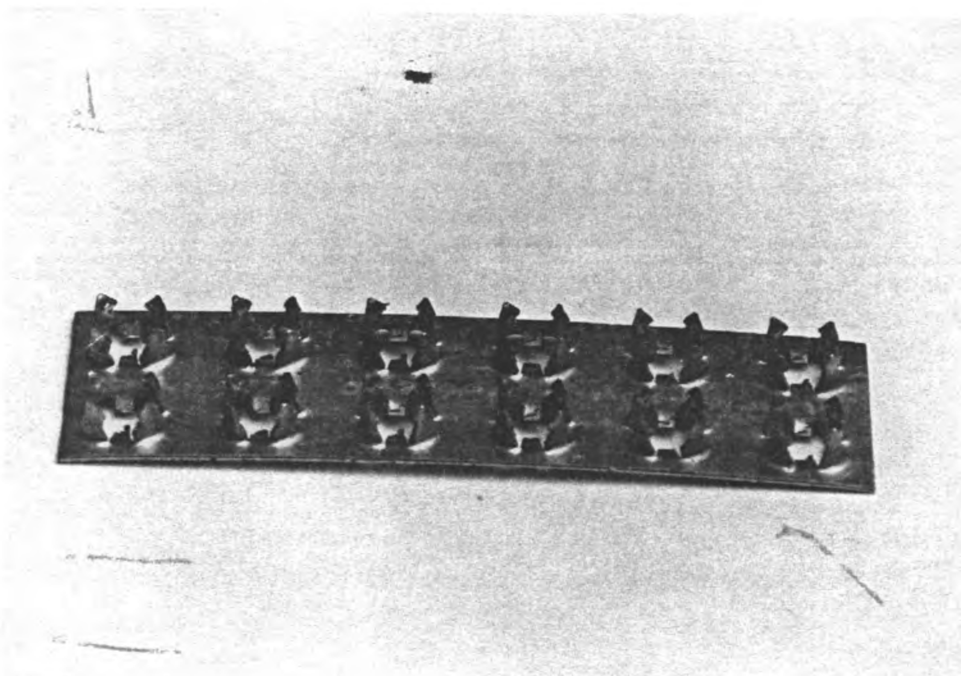

Figure 3.8. Plate AN2

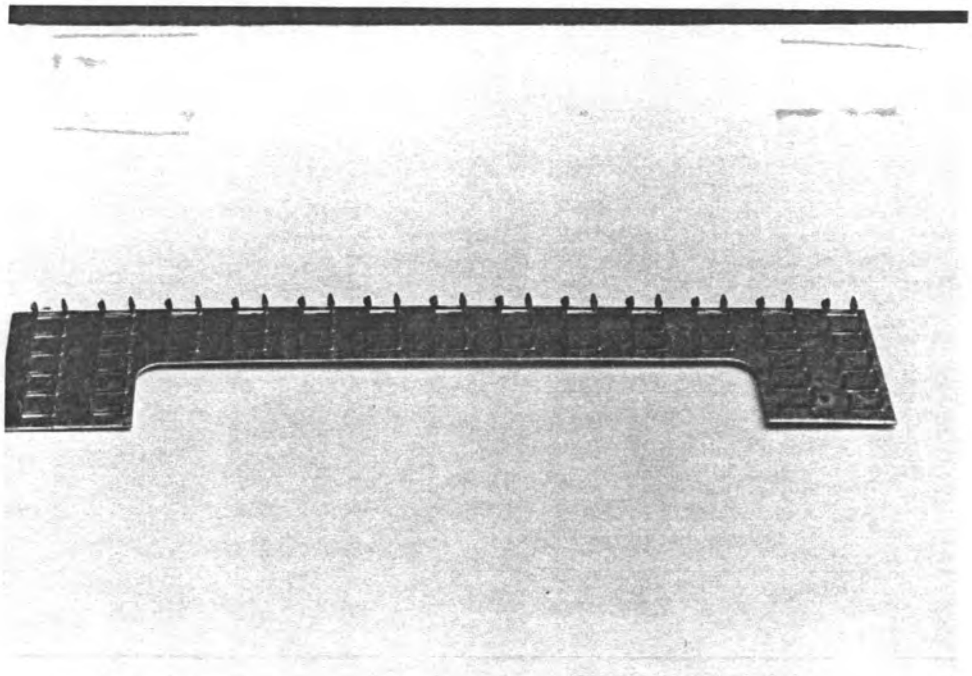

Figure 3.9. Plate AN3

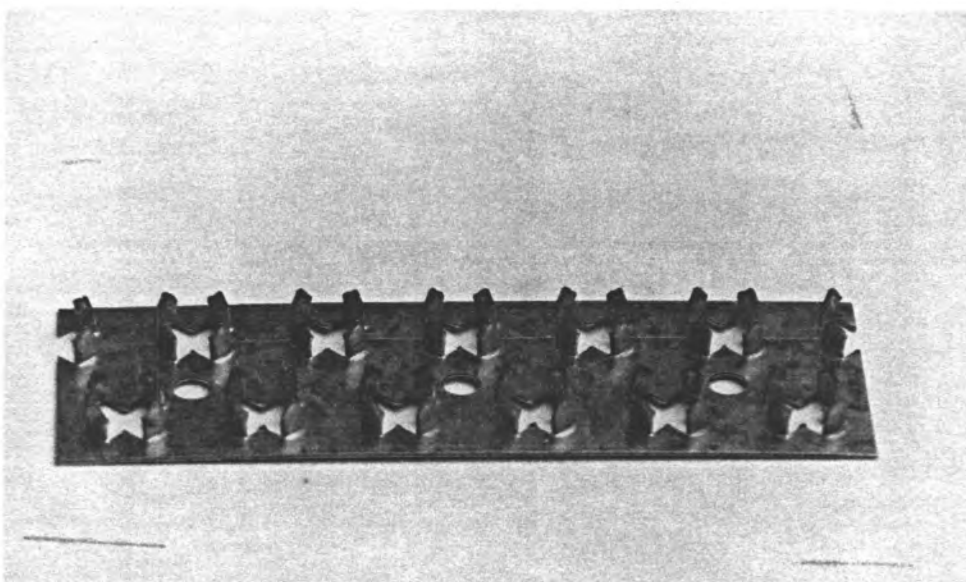

Figure 3.10. Plate AN4

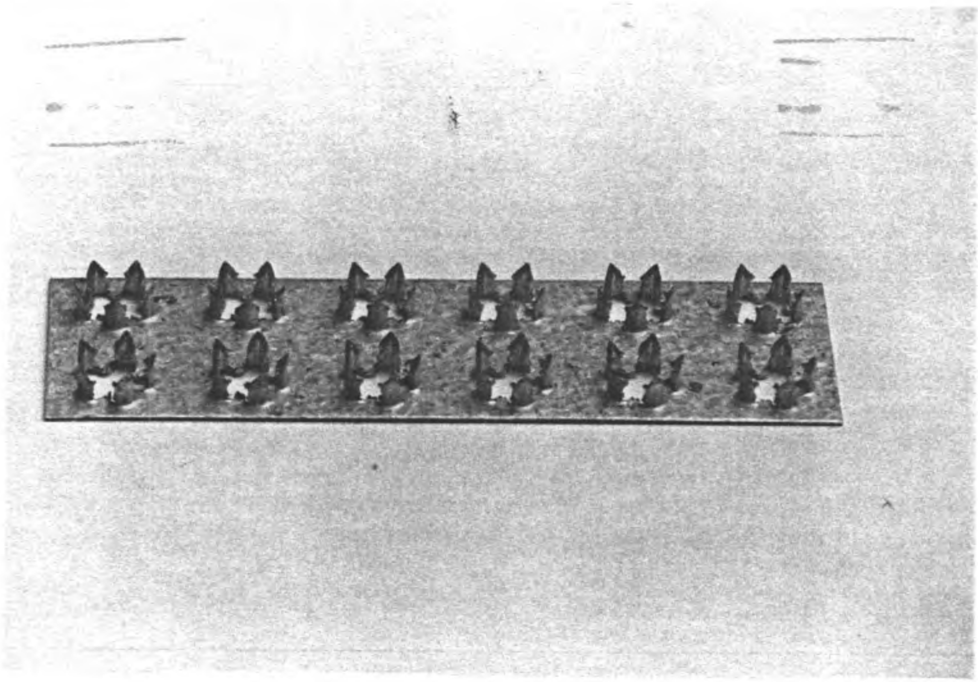

Figure 3.11. Plate AN5

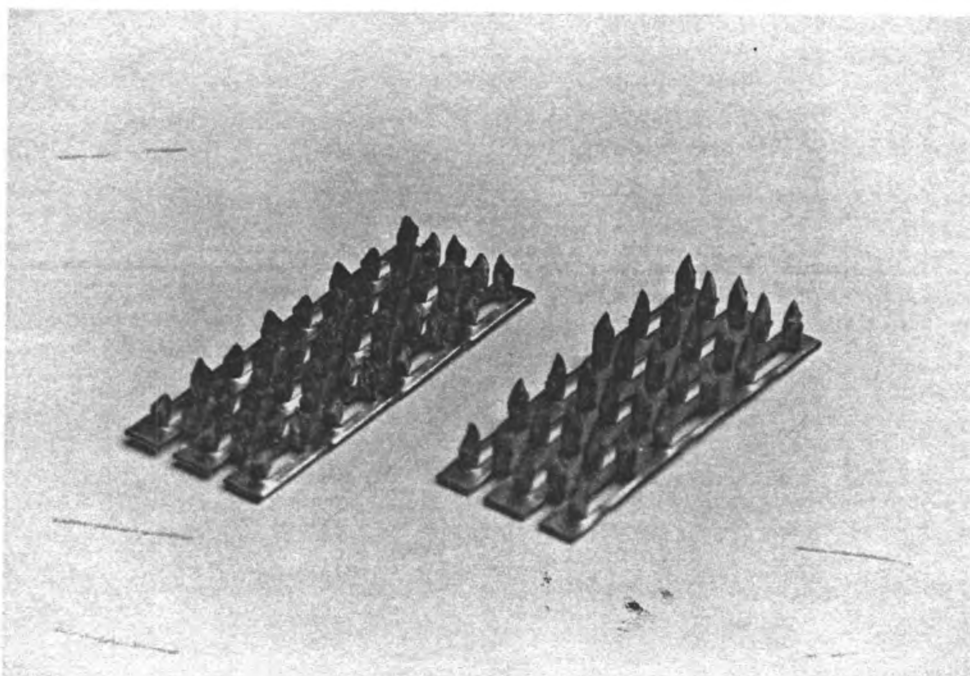

Figure 3.12. Plates EG1,EG2

The performance of most MCPs was evaluated using pallet components: stringers, notched stringer segments, and stringer end feet (see Figure 3.13). These components are described in Section 3.1. Assembled pallets were also tested for preliminary verification of the results from component testing. Test pallets and pallet components were sampled from inventory at selected pallet manufacturing sites in Virginia.

All test MCPs (except EG1 and EG2) were applied to pallet components with an Alpine Mity-Mite hydraulic truss-chord plater (see Figure 3.14). This machine was not designed for, or capable of, repair and reinforcement of whole pallets, but was acceptable for installing MCPs on pallet components. Typically, a sample was laid flat on the press table, and the fracture, if any, was closed by pressure from an air cylinder. A MCP was placed over the closed fracture and pressed in with a hydraulic ram. The sample was then turned over and the same process used to plate the opposite side. End-grain MCPs were applied by the plate manufacturer, using a hydraulic ram to press a single plate into each end of a full stringer. MCPs were applied to full pallets with a Clary scissors-jaw type pallet plater by Pallet Repairs of North Carolina.

3.3.1 Repair

Pallets and components for repair testing were dried to 12% MC (to represent used pallets), tested to failure to determine initial performance, repaired with MCPs, and then retested to failure to determine repaired performance. Each sample was tested twice, initially and after repair.

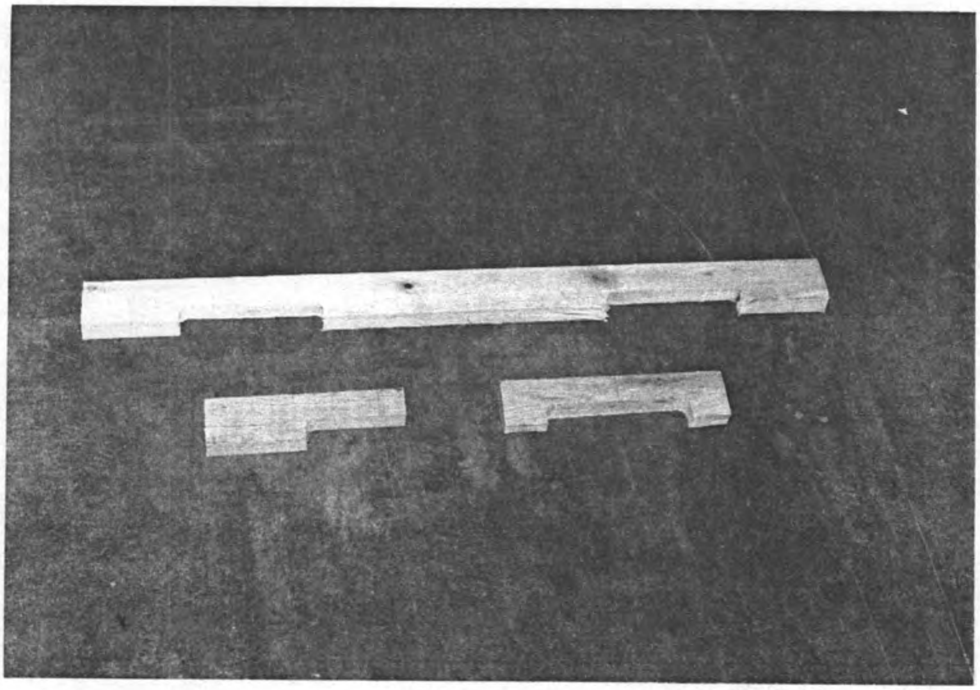

Figure 3.13 Pallet Components Used for MCP Evaluation

The Interim Guidelines for the Use of Pallet Metal Connector Plates published by the NWPCA [see Appendix A] were used to determine the method and number of MCPs used in stringer repair. For fractures less than 8 inches in length, 1 pair of plates were used, located at the notch where the fracture originated, and on opposite sides of the stringer. For fractures longer than 8 inches, 2 pairs of plates were used, one pair at the fracture origin and one pair at the fracture end. Depending on the fracture, the second pair could be placed anywhere from the middle of the stringer to the opposite notch.

All notched stringer segments and stringer end feet were repaired with 1 pair of MCPs. Plates for notched segments were centered over the notch. Side plates for end feet were located 1 inch from the impact end. Plates for both notched segments and end feet were located one on each side, and opposite each other. There were never more than two MCPs applied to any one notched stringer segment or end foot.

All fractures were mechanically-closed before plating, unless otherwise stated. An air piston attached to the Alpine plater (see Figure 3.15) was used for the mechanical closing. This piston is similar to mechanical pistons on many pallet repair platers. The piston air pressure was set to 90 psi.

3.3.2 Reinforcement

Pallets and components for reinforcement testing were reinforced with MCPs while green to represent new pallets. Reinforced and unreinforced control samples were then dried to 12% MC before testing to failure. Samples in the reinforcement phase were tested only once, either reinforced or unreinforced.

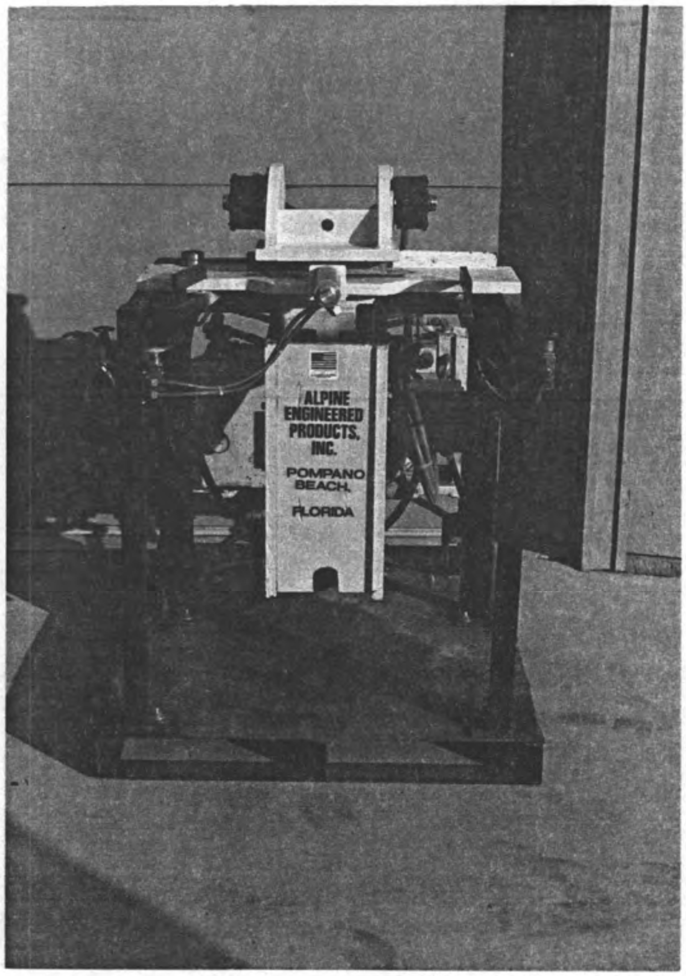

Figure 3.14 Hydraulic plater used for MCP application

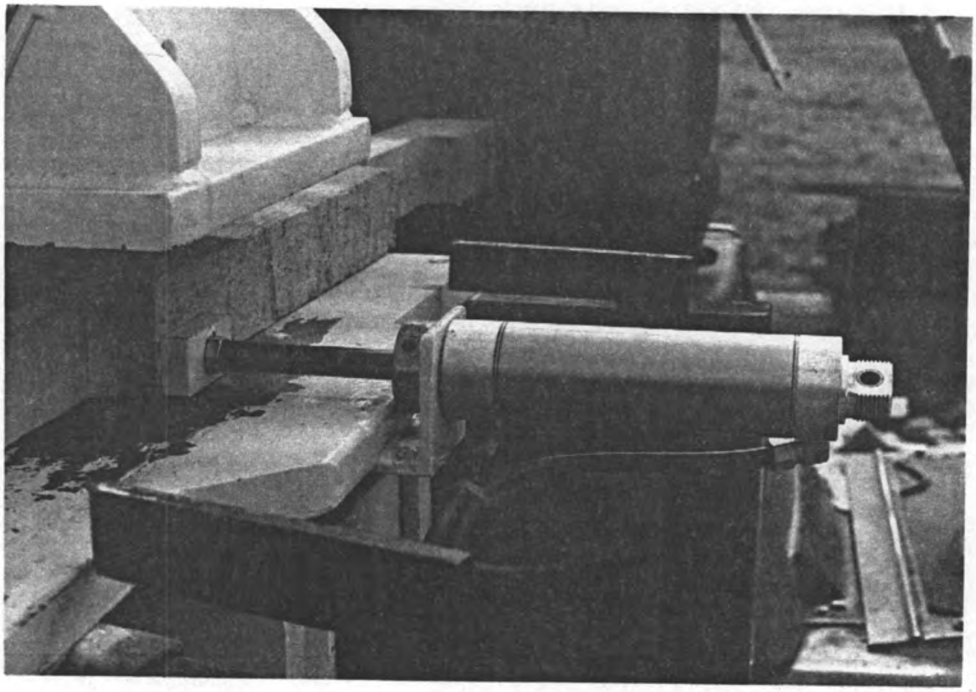

Figure 3.15 Air piston used for mechanical fracture closing

Reinforced stringers were plated with 2 pair of BN MCPs, one pair at each of the two inner notches, one plate on each side of the stringer. Reinforced end feet were plated with one pair of BN MCPs, located 1 inch from the impact end, one plate on each side of the foot. Notched stringer segments were not included in the reinforcement phase.

3.3.3 Full Pallets

For preliminary verification of results from testing of stringers, notched stringer segments, and end feet, a series of bending and rough handling tests with full pallets was conducted. The results of these pallet tests provided comparative damage resistance data and explored whether the static and dynamic tests adequately characterized damage.

Oak and YP pallets were manufactured from green material as is typical of commercial practice. SYP pallets were manufactured from dry material (approximately 20% MC), as SYP pallet shook is often purchased as kiln-dried stock rejected from other applications.

Fifteen replicate flush, 48x40-inch, partial 4-way, stringer-class pallets, five manufactured from each of the three wood species (oak, SYP, and YP) were fabricated. The following configurations were tested for each species.

1. Control pallet
2. Metal Connector Plate reinforced pallet
3. Metal Connector Plate repaired pallet
4. NWPCA Logo-Mark R-2 Grade repaired pallet
   (full-stringer companion)
5. NWPCA Logo-Mark R-3 Grade repaired pallet
   (half-stringer companion)

All stringers were 1½" wide. Top and bottom leading edge deckboards were 6" wide. Five 4" deckboards were evenly spaced along the top, and three 4" deckboards were evenly spaced in the bottom middle foot area. Deckboards were hand-nailed to stringers using common specifications of 3 nails per stringer with 6" deckboards, and 2 nails per stringer with 4" deckboards [3]. All deckboards were ⅝" thick. The nails were Philstone brand, 2¼" long, 0.112" diameter, hardened steel, helically threaded, with a diamond point (VPI # 2496).

One pallet of each species was set aside as a control. One pallet of each species was initially reinforced with MCPs. Plates were applied to each stringer with the Alpine Mity-Mite plater before pallet assembly. There were three stringers per pallet with four MCPs per stringer, one pair located at each inner notch. The three remaining pallets of each species were tested to failure, then repaired with one of the three methods.

The MCP-repaired pallets were plated with a Clary scissors-type plater with a mechanical piston to close fractures. Both BN and AN plates were needed. The Interim Guidelines for the Use of Pallet Metal Connector Plates published by the NWPCA [see Appendix A] were used to determine the method and number of MCPs used in stringer repair. For fractures less than 8 inches long, 1 pair of plates was used, located at the notch where the fracture originated, and on opposite sides of the stringer. For fractures longer than 8 inches, 2 pairs of plates were used, one pair at the fracture origin and one pair at the fracture end. Depending on the fracture, the second pair could be placed anywhere from the middle of the stringer to the opposite notch. All above notch fractures were plated with one pair of plates, centered over the notch and on opposite sides of the stringer.

For the R2 Grade Repair [3], full stringers were placed next to the fractured stringer and nailed to the deckboards. For the R3 Grade Repair, half-stringers were placed next to the fractured end of a stringer and nailed to the deckboards. Nails were Philstone brand, 2¼" long, 0.112" diameter, hardened steel, helically threaded, and diamond point (VPI # 2496).

3.4 STATIC BENDING TESTS

3.4.1 Experimental Design

A. Static Tests - Metal Connector Plate Repair

Full stringers and notched stringer segments were initially tested while undamaged to determine the original strength and stiffness. Broken samples were then classified by fracture characteristics [see Appendix B] and assigned to subset treatment groups. After repair with MCPs, the samples were retested in static bending to determine the repaired strength and stiffness.

Table 3.2 gives an overview of the experimental plan for static bending tests of MCP-repaired stringers and notched stringer segments.

<u>Effect of Plate Design</u>

Hypothesis: There was no significant effect of MCP design on the static bending properties of either MCP-repaired stringers or notched stringer segments.

Current NWPCA interim plate-repair guidelines [see Appendix A] make no

Table 3.2: Experimental Design - Static Tests - Repair Phase[1,2]											
Subset	Stringer Between Notch Tests						Notched Segment Above Notch Tests				
Plate Styles:	BN1	BN2	BN3	BN4	BN5	BN6	AN1	AN2	AN3	AN4	AN5
a. Plate Design	30_a	30	30	30_b	30_c	30	30	30_d	30	30	30
b. Fracture Closing											
hand closing	30	-	-	30	30	-	-	-	-	-	-
mechanical	a	-	-	b	c	-	-	-	-	-	-
c. Fracture Length[3]											
Class IA1	30	-	-	-	-	-	-	-	-	-	-
Class IA2	30	-	-	-	-	-	-	-	-	-	-
Class IA3	30	-	-	-	-	-	-	-	-	-	-
Class IA4	30	-	-	-	-	-	-	-	-	-	-
Class IIB1	-	-	-	-	-	-	-	30	-	-	-
Class IIB2	-	-	-	-	-	-	-	30	-	-	-
Class IIB3	-	-	-	-	-	-	-	30	-	-	-
Class IIB4	-	-	-	-	-	-	-	30	-	-	-
d. Species/Width											
1½" oak	a	-	-	-	-	-	-	d	-	-	-
SYP[4]	40_e	-	-	-	-	-	-	40_h	-	-	-
2½" oak	30_f	-	-	-	-	-	-	30_i	-	-	-
SYP	40_g	-	-	-	-	-	-	40_j	-	-	-

[1] All samples were tested twice, originally and after repair with MCPs. Only 1½" wide oak was tested unless otherwise stated.

[2] Some treatment groups were repetitive. To avoid redundant testing, these groups were assigned a subscript. When the treatment group results were used in later subsets, the subscript is listed alone.

[3] For description of fracture classes, see Appendix B.

[4] SYP = southern yellow pine

distinction between the various MCP sizes and tooth designs. This experimental subset determined if a significant difference existed between the various designs, and if differences did exist, which designs were more effective for MCP repair.

To determine the effect of plate design on repaired stringer performance, 6 BN plates and 5 AN plates were evaluated. These plates were selected to represent the various designs and manufacturers currently in production for the pallet market. Table 3.1 and Figures 3.1-3.12 describe the MCPs. Each MCP was assigned to a treatment group of 1½" wide oak stringers.

Effect of Mechanical Fracture Closing

Hypothesis: There was no significant difference between the two fracture closing methods (hand-pressure and mechanical-pressure) on the static bending properties of MCP-repaired stringers.

Only BN fractures in full stringers were evaluated in this subset. The typical AN fractures from our tests could not be closed by the mechanical piston on repair machines.

There were two basic methods of closing a BN stringer fracture before MCP repair: closing by hand-pressure or mechanically closing with a piston on the repair machine (see Figure 3.15). Current NWPCA interim plate-repair guidelines [see Appendix A] require a mechanically-closed fracture before MCP repair. This subset determined if the mechanical-closing requirement is necessary.

Testing in the plate design subset determined that the plates were statistically similar for bending strength. Therefore, the three MCPs (BN1,BN4, and BN5) for this subset were selected to represent the range of tooth styles. All stringer fractures in the plate design subset were mechanically-closed. To avoid redundant tests, the mechanically-closed fracture treatment groups were the three plate design groups corresponding to BN1, BN4, and BN5 (subscripts a,b,c). These same three MCPs were assigned to repair three other 1½" wide oak treatment groups using hand-pressure fracture closing. The mechanically-closed group for each MCP was compared with the hand-closed group with the same MCP.

Effect of Fracture Length

Hypothesis: There was no significant difference between the static bending properties of either MCP-repaired stringers or notched stringer segments with different fracture lengths.

In other subsets, repair of full stringers followed NWPCA interim pallet-repair guidelines [see Appendix A], which call for 2 pair of MCPs if fracture length is greater than 8 inches. In this subset, all full stringers were repaired with one pair of MCPs located at the fracture origin. Any significant differences in bending properties between the stringers with different fracture lengths would indicate whether the use of more than one pair of MCPs is justified.

Due to specimen size, only one pair of MCPs was possible for AN fractures. Significant differences in bending properties due to AN fracture length may help determine a fracture length beyond which AN repair is ineffective.

One BN plate style and one AN plate style were evaluated for this subset. No significant differences existed in earlier subsets for bending strength between the plate designs. Plates BN1 and AN2 were selected for the typical plug-tooth design of pallet plates.

Eight treatment groups of 1½" wide oak were formed by fracture type, one for each of BN Classes IA1,IA2,IA3,and IA4 and AN Classes IIB1,IIB2, IIB3,and IIB4 [see Appendix B for fracture descriptions].

Effect of Species/Width

Hypothesis: There was no significant difference in the repaired performance of either MCP-repaired stringers or notched stringer segments due to species or width.

The current NWPCA interim plate-repair guidelines [see Appendix A] contain no species or width restrictions. This subset determined if the static bending properties of repaired components were influenced by species characteristics or width differences.

Plates BN1 and AN2 were evaluated. Samples of two widths, 1½" and 2½", and two species, oak and SYP, were evaluated. Comparison treatment groups for 1½" wide oak came from the corresponding treatment groups in the plate design subset (subscripts a,d).

B. Static Tests - Metal Connector Plate Reinforcement

Only full stringers were evaluated in static MCP-reinforcement tests. The purpose of reinforcement testing was to compare the static bending properties of MCP-reinforced stringers with the static bending properties of unreinforced stringers drawn from the same population. There was no repair or retesting. Plate BN1 was selected for all reinforcement. Bending strength of this plate was statistically similar to the other plate designs, and the smaller size (price?) may make it more attractive for reinforcement.

Table 3.3 gives an overview of the tests for static bending of MCP-reinforced and unreinforced full stringers.

Effect of Species/Width

Hypothesis: There was no significant effect on the bending performance of MCP-reinforced stringers due to species or width.

Current NWPCA interim plate-reinforcement guidelines [see Appendix A] contain no species or width restrictions. This subset determined if MCP reinforcement was influenced by species or width factors. Stringers of three species (oak, SYP, and YP) and two widths (1½" and 2½") were assigned to treatment groups and reinforced with plate BN1.

Species Substitution

Hypothesis: There was no significant difference between the static bending properties of MCP-reinforced stringers of Class B pallet species and unreinforced stringers of Class C pallet species.

Class B and Class C refer to the NWPCA ranking of pallet components, based on density [6].

Table 3.3: Experimental Design - Static Tests - Reinforcement Phase[1,2]		
Subset	Unreinforced	Reinforced Plate BN1
a. Stringer Species/Width		
1½" oak	-	30_k
SYP[3]	-	40_l
YP[3]	-	30_m
2½" oak	-	30_n
SYP	-	40_o
b. Species Substitution		
1½" oak	a	-
SYP	-	l
YP	-	m

[1] All stringers were tested only once. Stringers were either reinforced or unreinforced.

[2] Some treatment groups for both repair and reinforcement were repetitive. To avoid redundant testing, these groups were assigned a subscript. When the treatment group results were used in later subsets, the subscript is listed alone.

[3] SYP = southern yellow pine; YP = yellow poplar

This subset determined if a weaker species could be reinforced to equal the static bending performance of a stronger, unreinforced species.

Class B reinforced stringers (SYP and YP) were compared to Class C (oak) unreinforced stringers. The treatment group for unreinforced oak came from the stringer repair plate design subset (subscript a). Treatment groups for MCP-reinforced SYP and YP came from the stringer reinforcement species/width subset (subscripts l,m).

3.4.2 Specimen Selection

A. Specimen Selection - Stringer Repair

A total of 500 full stringers were tested in static bending. The key subsets of the experimental design shown in Table 3.2 and are: **A.** effect of plate design (180 replicates, 1½" wide Oak), **B.** effect of mechanical fracture closing (90 reps., 1½" wide Oak), **C.** effect of fracture length (120 reps., 1½" wide Oak), and **D.** effect of stringer species/width (30 reps., 2½" wide Oak, 40 reps., 1½" wide SYP, and 40 reps., 2½" wide SYP).

One treatment group was needed for each factor level in each subset. Thirty replicates were needed for each treatment group of oak stringers based on the variability seen in the initial static bending tests of undamaged stringers [see Appendix C]. Southern yellow pine (SYP) stringers, however, exhibited more variability in bending strength and forty replicates were required for each treatment group.

A total of 16 treatment groups were needed for between notch repair of full stringers; 13 of 1½" wide oak, 1 of 2½" wide oak, 1 of 1½" wide SYP, and 1 of 2½" wide SYP. The experimental design required that all test groups of 1½" wide oak stringers within a subset have statistically similar initial static bending properties in order to obtain valid comparisons between groups. The 1½" wide oak stringers were tested to determine initial static bending properties before assignment to treatment groups. No attempt was made to use a nondestructive evaluation (NDE) parameter, such as stiffness, to assign stringers to groups. Stiffness is poorly correlated to notched stringer strength because failure is localized at the notch area.

Initially, 300 stringers, assigned to evaluate the plate design and fracture length subsets, were dried and tested to failure in static bending. The 300 broken stringers were grouped according to the fracture characteristics [see Appendix B]. Only straight, between-notch (BN) fractures (IA1,IA2,IA3,IA4) were desired for MCP repair evaluation. Load at failure (strength) was the static bending property deemed most important for group comparisons. Within the four BN fracture levels, the stringers were ranked by bending strength, from low to high. The 15 stringers with the greatest strength and the 15 stringers with the lowest strength for each BN fracture level were assigned to the fracture length subset (four levels of thirty replicates each). The result was four groups of 1½" wide oak stringers with statistically similar initial distributions of strength for test of the effect of four different fracture lengths on stringer performance [see Appendix D.2].

The remaining 180 stringers were designated for the plate design subset. To ensure uniformity in the six plate design groups, the stringers (which were still ranked by strength) were assigned a number (1-6, 6-1, 1-6, etc.), until 30 stringers had been assigned to each number. The result was six treatment groups of stringers with statistically similar distributions of strength for comparing the six types of MCPs in the plate design subset [see Appendix D.1].

The remaining 90 1½" oak stringers were dried after the 300 1½" wide oak stringers and designated for the fracture closing subset. These ninety stringers were blocked by fracture characteristics and ranked by bending strength as above. Stringers were assigned a number (1-3,3-1, etc.) to partition equally into three treatment groups for the 3 MCPs that were compared in the fracture closing subset [see Appendix D.3].

The remaining treatment groups were for the stringer species/width subset and were all unique. One treatment group for each of 2½" wide oak, and 1½" and 2½" wide SYP were used, and there was no blocking or ranking by load. Treatment groups were not statistically similar [see Appendix D.4], but the fracture lengths resulting from the initial failures were similar.

B. Specimen Selection - Notched Segment Repair

A total of 360 notched stringer segments were tested in static bending. The key subsets of the experimental design shown in Table 3.2 are: **A.** effect of plate design (150 replicates, 1½" wide oak), **B.** effect of fracture length (120 reps., 1½" wide oak), and **C.** effect of stringer species/width (30 reps., 2½" wide oak, 40 reps., 1½" wide SYP, and 40 reps., 2½" wide SYP). Thirty replicate segments for oak and forty for SYP were needed for each treatment group based on initial tests with unbroken segments [see Appendix C].

A total of 12 treatment groups were needed for notched segment repair, 9 of 1½" wide oak, 1 of 2½" wide oak, 1 of 1½" wide SYP, of 1 of 2½" wide SYP. The experimental design required that treatment groups of 1½" wide oak segments within subsets have statistically similar initial static bending strengths.

Initially, 270 1½" wide oak segments were tested to failure in static bending. The broken segments were classified according to fracture characteristics [see Appendix B for fracture descriptions]. Only sloped, above-notch (AN) fractures were desired for MCP repair (Classes IIB1,IIB2,IIB3,IIB4). The 270 segments were then ranked within each fracture class by bending strength, from low to high. Strength was deemed the more important indicator of segment performance.

Nine treatment groups of 30 1½" wide oak segments were needed. Four of the treatment groups for the fracture length subset were to include only one type of fracture each. As with full stringers, the first 15 and last 15 segments in each fracture type (IIB1, IIB2, IIB3, IIB4) were designated for the four factor levels for the fracture length subset. Statistical analysis confirmed the four groups were similar with respect to strength [see Appendix D.6]. Five remaining treatment groups were needed, so the segments (ranked by strength), were assigned a number (1-5, 5-1, 1-5, etc.), until 30 segments were assigned to each number. This resulted in 5 treatment groups to compare the 5 styles of AN plates [see Appendix D.5].

As with full stringers, the treatment groups for segment species/width were all unique. One treatment group for each of 2½" wide oak, 1½" wide SYP, and 2½" wide SYP segments were used, and there was no blocking or ranking by load. Treatment groups are compared in Appendix D.7. Initial fracture lengths were similar for all groups except 2½" wide SYP, which had a longer average fracture length.

C. Specimen Selection - Stringer Reinforcement

A total of 200 full stringers were tested in static bending. The key subsets for full stringer reinforcement shown in Table 3.3 are: **A.** effect of stringer species/width (30 replicates, 1½" wide reinforced oak, 30 reps., 2½" wide reinforced oak, 40 reps., 1½" wide reinforced SYP, 40 reps., 2½" wide reinforced SYP, 30 reps., 1½" wide unreinforced YP, and 30 reps., 1½" wide reinforced YP), and **B.** species substitution. Thirty replicates were required for each treatment group of oak and YP stringers, based on initial testing of new, unbroken stringers [see Appendix C]. SYP stringers, however, exhibited more variation in their strength, and required 40 replicates per treatment group for the experimental design.

A total of 6 treatment groups were needed for full stringer reinforcement; 1 of 1½" wide reinforced oak, 1 of 2½" wide reinforced oak, 1 of 1½" wide reinforced SYP, 1 of 2½" wide reinforced SYP, 1 of 1½" wide reinforced YP, and 1 of 1½" wide unreinforced YP. All treatment groups for full stringer reinforcement were unique, and as stringers were tested only once, no blocking or ranking was needed. Stringers of each species and width were assigned at random to the treatment groups before testing. Random assignment was used rather than distribution using a nondestructively evaluated variable such as stiffness. This is because of the poor correlation between notched stringer strength and stiffness. Statistical analysis confirmed that the reinforced and unreinforced counterpart groups were similar [see Appendix D.8].

3.4.3 Test Setup - Static Bending Tests

Both failures between the notches (BN) and failures above the notch (AN) were considered. The third-point static bending test outlined in ASTM D-198-84 [18] was used for tests of full stringers. This test will usually result in a BN failure, where a crack initiates at the inner notch fillet. AN failures are also possible. To consistently create AN failures, however, center-point bending tests of notched stringer segments cut from the full stringer were made. All stringers designated for reinforcement were tested using the third-point bending test described in ASTM D 198-84.

Full stringers were supported over a span of 45" and loaded at the third-points with a rate of 1 inch/minute (see Figure 3.16). A MTS servo hydraulic test machine under stroke control was used for all static testing. No lateral support was needed.

A Hewlett-Packard flat-bed X-Y recorder graphed load versus deflection. Load was defined as resistance to the downward movement of the ram, measured directly by a load cell. Two different deflection measurement schemes were considered for the bending tests. The first method measured stringer deflection at midspan with a LVDT suspended on a yoke-type hanger, similar to that proposed by ASTM D-198, Section 7.4.3 [18]. Alternatively, the recorded movement of the hydraulic ram was compared to the centerline deflection. These comparisons indicated that there was only a 2% average difference between the two deflection measurements over a range of 0-1½ inches of deflection. While there was some inherent error in the internal ram measurement, the

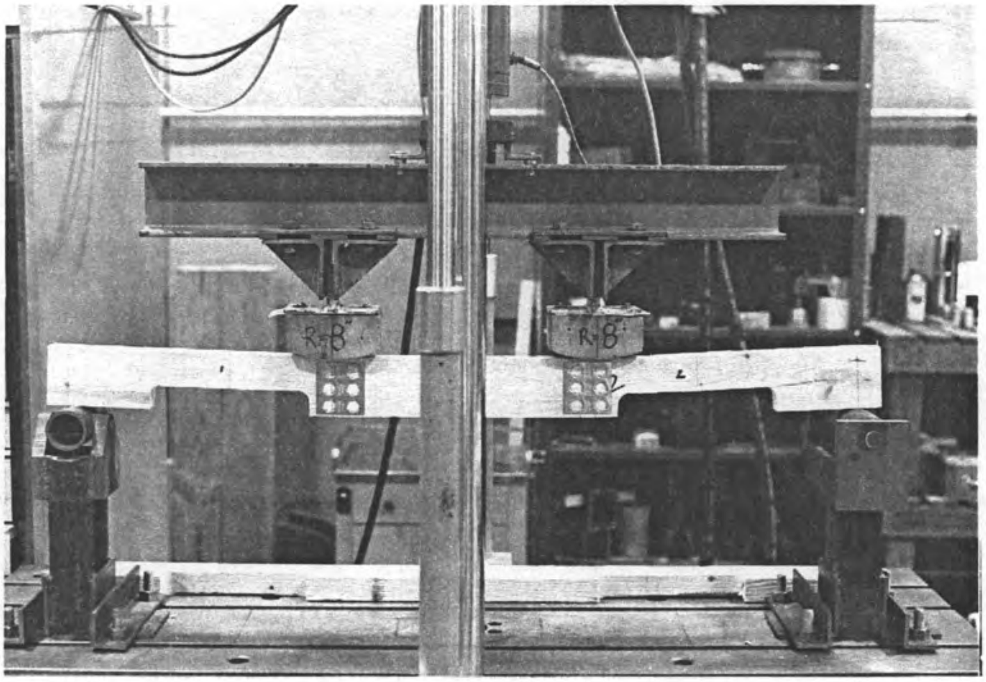

Figure 3.16 Bending Test Setup for Stringers

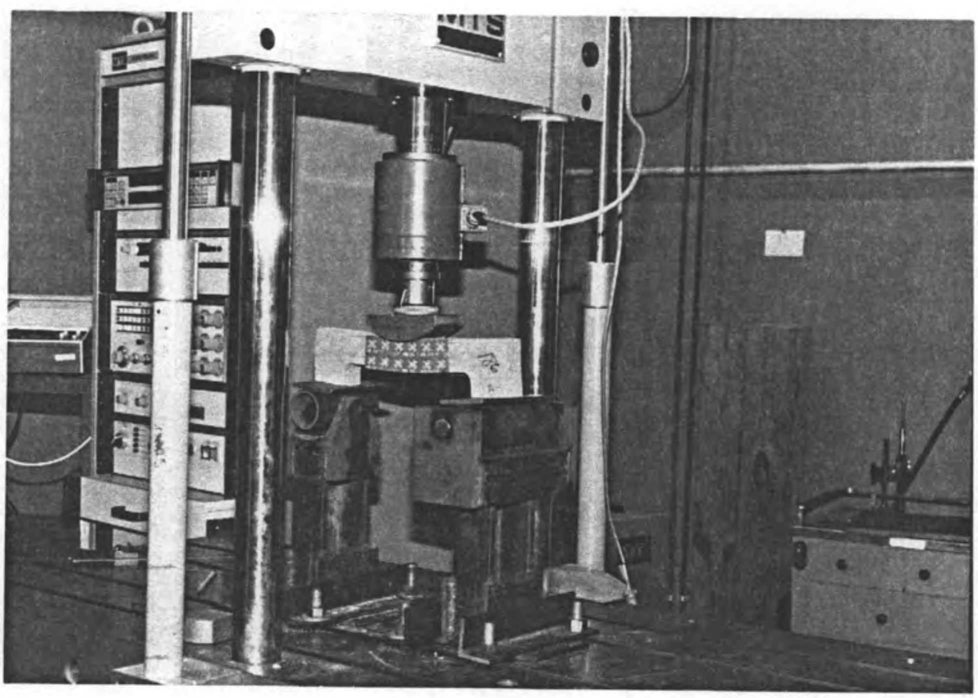

Figure 3.17 Bending Test Setup for Notched Segments

interest was in relative, not absolute, comparisons and this error was acceptable. To speed testing the internal MTS ram movement was used for all deflection readings.

Notched stringer segments were supported over a 12 inch span and loaded at the center-point at a rate of 1 inch/minute (see Figure 3.17). No lateral support was needed, and an analog record of ram load versus ram deflection was made. All full stringers and notched segments were measured with calipers to determine actual cross-section dimensions to nearest 0.01 inch. Moisture content was measured on each sample with a Delmhorst RDX-1 moisture meter immediately before each test. Specific gravity samples were taken after testing using water immersion (Method B-II as described in ASTM D-2395 [27]).

3.5 DYNAMIC IMPACT TESTS

3.5.1 Experimental Design

A. Dynamic Impact Tests - Metal Connector Plate Repair

Repaired end foot tests required that the end feet initially be tested undamaged and unplated to determine original impact resistance. Impact resistance is defined as the number of impacts of a fork tine on the end foot required to cause failure as described in Section 3.6.3. Broken samples were assigned to treatment groups. After repair with MCPs, the end feet were retested to determine repaired impact resistance.

Although the designation "BN" refers to "between the notch", and BN plates were tested earlier on stringers, they were also used for end foot repairs. The 6 BN MCPs from Table 3.1 were the possible MCPs for end foot repair.

The static bending of repaired stringers phase, completed prior to the dynamic impact phase, indicated no significant differences in the strength of stringers repaired with the six plate designs. There is no assurance, however, that these results would hold for dynamic impact resistance. The X-shaped plug (plate BN4) and a truss-tooth (plate BN5) design were selected for impact tests of repaired end feet.

Table 3.4 gives an overview of the tests for impact performance of MCP-repaired end feet.

Effect of Plate Design

Hypothesis: There is no significant effect of plate design on the impact resistance of MCP-repaired end feet.

Current NWPCA interim plate-repair guidelines [see Appendix A] make no distinction between MCP design and tooth styles. This subset determined if a significant difference existed between the performance of two designs, and if a difference existed, which design was more effective for end foot repair.

Two MCPs were evaluated, BN4 and BN5. Table 3.1 and Figures 3.4,3.5 describe and illustrate the plates. Each of these plates was assigned to a treatment group of 1½" wide oak.

Effect of Fracture Type

Hypothesis: There was no significant difference between one-piece and two-piece end foot failures repaired with MCPs.

TABLE 3.4: Experimental Design - Dynamic Tests - Repair Phase[1]		
Subset	End Foot Tests	
	Plate BN4	Plate BN5
a. Plate Design	20_p	20
b. Fracture Type[2]		
Class IIIA	20	-
Class IIIB	20	-
c. Species/Width		
1½" oak	p[4]	-
SYP[3]	20_q	-
2½" oak	20_r	-
SYP[3]	20_s	-

[1] All End Foot Repair samples were tested twice, originally and after repair with MCPs. Only 1½" wide oak was tested unless otherwise stated.
[2] for description of fracture classes, see Appendix B.
[3] SYP = southern yellow pine
[4] Some treatment groups were repetitive. To avoid redundant testing, these groups were assigned a subscript. When the treatment group results were used in later subsets, the subscript is listed alone.

TABLE 3.5: Experimental Design - Dynamic Tests - Reinforcement Phase[1,2]		
Subset	Unreinforced	Reinforced
		Plate BN1
a. Species/Width		
1½" oak	p	20
SYP[3]	q	20
YP[3]	20	20
2½" oak	r	20
SYP[3]	s	20

[1] All Reinforced End Feet were tested only once. Samples were either reinforced or unreinforced.
[2] Some treatment groups for Dynamic Tests - Repair and Reinforcement were repetitive. To avoid redundant testing, these groups were assigned a subscript. When the treatment group results were used in later subsets, the subscript is listed alone.
[3] SYP = southern yellow pine, YP = yellow poplar

Two fracture types were desired, a fracture that split the end foot but left it in one piece, and a fracture that extended to the notch fillet area and resulted in a two-piece end foot [see Appendix B, Class IIIA and Class IIIB]. In order to consistently create the two fracture types, a different initial impact location was required for each group. The two fracture types were not formed randomly, but by the location of initial impact. End feet were impacted 2½" below the top edge for one-piece fractures, and 2" below the top edge for two-piece fractures. For this subset only, repaired end feet were impacted 1" below the top edge.

The lower impact resistance performer (BN4) from the end foot plate design subset above was selected for the fracture type subset. Oak end feet, 1½" wide, were randomly assigned to the two treatment groups, then impacted for either a one-piece or two-piece failure.

Effect of Species/Width

Hypothesis: There was no significant difference in the repaired performance of MCP-repaired end feet due to species or width.

Current NWPCA interim plate-repair guidelines [see Appendix A] contain no species or width restrictions. This subset determined if MCP repair of end feet was influenced by species or width factors.

Plate BN4 was used for this subset. End feet were impacted as they were in the plate design subset.

Treatment groups of two species, oak and SYP, and two widths, 1½" and 2½", were evaluated. To avoid redundant testing, the treatment group for 1½" wide oak came from the end foot plate design subset (subscript p). A treatment group was tested for each of the other species and widths.

B. Dynamic Impact Tests - Metal Connector Plate Reinforcement

The purpose of reinforcement testing was to compare the impact resistance of reinforced end feet with the impact resistance of unreinforced end feet from the same initial population. End feet were tested only once; there was no repair or retesting.

End foot repair testing was completed prior to end foot reinforcement testing. The two plates evaluated in end foot repair (BN4 and BN5) exhibited different levels of impact resistance. Use of either plate was acceptable, however, since the MCP-repaired end feet had significantly more impact resistance (RP = 150-320%) than the original end feet. Plate BN5 had a truss-type tooth design; plate BN4 had a X-shaped plug tooth design. Since the BN4 and BN5 tooth designs were acceptable for end foot repair, a round plug tooth design was desired for end foot reinforcement. Plate BN1 gave acceptable repair and reinforcement in the static bending of stringers, and was smaller than the other round plug plates. Therefore, BN1 was selected for end foot reinforcement.

Table 3.5 gives an overview of the impact tests of MCP reinforced end feet.

Effect of Species/Width

Hypothesis: There was no significant effect of different species and widths on the impact performance of end feet reinforced with plate BN1.

Current NWPCA interim plate-reinforcement guidelines [see Appendix A] contain no species or width restrictions. This subset determined if end foot MCP reinforcement was influenced by species or width factors.

Plate BN1 was used for this subset. Treatment groups for reinforced 1½" wide oak, SYP, and YP, and 2½" wide oak and SYP were tested. A treatment group of 1½" unreinforced YP was also tested, and treatment groups for unreinforced oak and SYP were from end foot repair (subscripts p, q, r, s).

Species Substitution

Hypothesis: There was no significant difference between the impact resistance of MCP-reinforced end feet of Class B pallet species and unreinforced end feet of Class C pallet species.

Class B and Class C refer to the NWPCA ranking of pallet components, based on density [6].

This subset determined if a weaker species could be reinforced to equal the impact resistance of a stronger, unreinforced species.

3.5.2 Specimen Selection

A. Specimen Selection - End Foot Repair

A total of 140 end feet were evaluated in the repair phase of dynamic impact testing. The key subsets for the end foot repair study phase are given in Table 3.4 and were: **A.** effect of plate design (40 replicates, 1½" wide oak), **B.** effect of fracture type (40 reps., 1½" wide oak), and **C.** effect of species/width (20 reps., 2½" wide oak, 20 reps., 1½" wide SYP, and 20 reps., 2½" wide SYP).

Twenty replicates were required for each treatment group, based on initial testing of new, unbroken end feet [see Appendix C]. A total of 7 treatment groups were needed for the end foot repair study; 4 of 1½" wide oak, 1 of 2½" wide oak, 1 of 1½" wide SYP, and 1 of 2½" wide SYP. The experimental design required that the 1½" wide oak treatment groups within the subsets be similar for initial impact resistance.

Forty 1½" wide oak end feet were randomly assigned to the two treatment groups in the plate design subset. After initial testing, statistical analysis confirmed that the two groups exhibited similar impact resistance [see Appendix D.9]. Each plate style was then assigned to one of the treatment groups.

Forty other 1½" wide oak feet were used in the fracture type subset. The two types of fractures were created by initially impacting the end feet at two different locations. Statistical analysis confirmed that the two groups had similar impact resistance [see Appendix D.10].

All other treatment groups for end foot repair were unique. Random samples of each species and width were assigned to treatment groups for the 2½" wide oak and the 1½" and 2½" wide SYP. Groups were not statistically similar [see Appendix D.11].

B. Specimen Selection - End Foot Reinforcement

A total of 120 end feet were evaluated in dynamic impact testing. The key subsets for end foot reinforcement are given in Table 3.5 and are: **A.** effect of species/width (20 replicates, 1½" wide reinforced oak, 20 reps., 1½" wide reinforced SYP, 20 reps., 2½" wide reinforced oak, 20 reps., 2½" wide reinforced SYP, 20 reps., 1½" wide reinforced YP, and 20 reps., 1½" wide unreinforced YP), and **B.** species substitution.

Twenty replicates were required for each treatment group based on initial testing of unbroken end feet [see Appendix C]. A total of 6 treatment groups were used for the end foot reinforcement study; 1 of 1½" wide reinforced oak, 1 of 2½" wide reinforced oak, 1 of 1½" wide reinforced SYP, 1 of 2½" wide reinforced SYP, 1 of 1½" wide reinforced YP, and 1 of 1½" wide unreinforced YP. All treatment groups for the end foot reinforcement study were unique. End feet were tested only once, either reinforced or unreinforced. Random samples of each species and width were assigned to the treatment groups before testing. Analysis confirmed that the reinforced and unreinforced counterparts were statistically similar [see Appendix D.12].

3.5.3 Test Setup - Dynamic Impact Tests

Stringer end feet for dynamic testing were samples cut from the end of stringers tested earlier in the static bending study. Stringers, tested in static bending, normally failed at one or both interior notches (BN fracture), leaving the two end feet intact. The end blocks were cut 12" long to include part of the notch area.

No quantifiable standard test method currently exists which simulates the dynamic impact of a forklift tine on a stringer end foot segment. ASTM D-1185 [22], Sections

43-48 (Fork-Tip Impact Resistance of Stringer or Block), outlines an impact test for end feet of stringers in fully assembled pallets. Due to the number of replicates, testing of full-size pallets was not feasible.

The end foot test method must quantify, in some manner, the impact resistance of end feet (energy absorbed before failure, number of blows before failure, etc.). Two methods were considered, one using the MTS servo hydraulic test machine, and the other an inclined impact tester.

A. MTS Tester

The MTS servo hydraulic test machine offers a reliable, time-proven method of strength and stiffness testing. However, available equipment limited the maximum striker speed to 0.2 mph over a ½ inch distance. This was not a true real-world impact, but did offer quasi-dynamic testing, accuracy, and reproducibility.

End feet were held in the notch area by a vise with the end to be impacted pointing up (see Figure 3.18). A simulated forklift tine, having a flattened, straight impact edge with width of 0.25 inch, was attached to the MTS crosshead. A single cycle movement of the ram under stroke control caused the end feet to fail in one impact. The quantitative measure was the amount of force required to travel the full stroke (i.e. the resistance of the end foot to fracture). Energy consumed could also be derived.

Preliminary tests were conducted on unplated 1½" wide oak and SYP end feet with satisfactory results. Tests were also conducted on 1½" wide oak and SYP end feet reinforced with end-grain MCPs (EG1,EG2). The simulated tine impact caused the

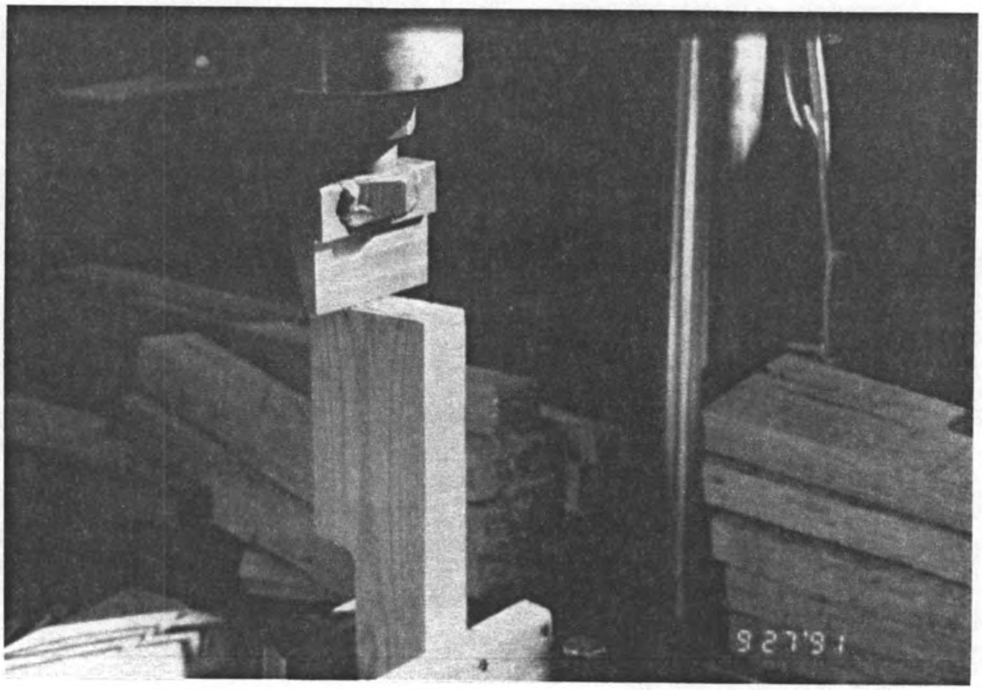

Figure 3.18 Test Setup for MTS Impact on End Feet

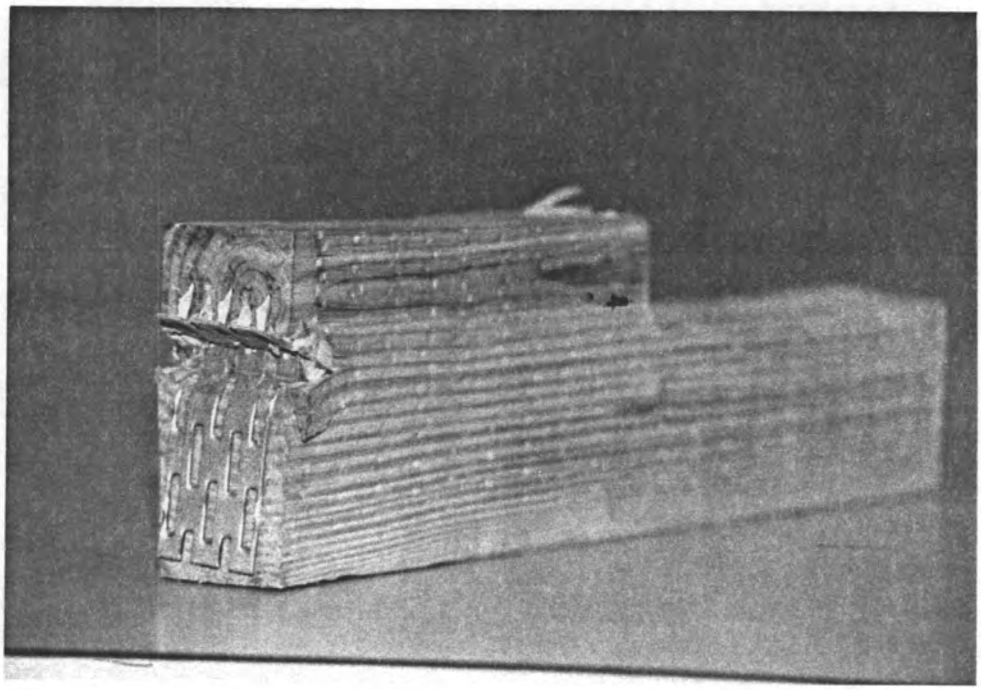

Figure 3.19 Curl Failures on End Grain MCPs

end grain plates to curl from the wood surface (see Figure 3.19), rendering the end of the foot unsafe for commercial use, possibly more unsafe than a broken end foot. The ram speed was slowed to 0.05 inch/minute, and it was determined that the MCP curl occurred before wood failure. Therefore, an end foot reinforced with an end grain plate would fail (by MCP curl) before an unreinforced end foot (by wood failure).

The question arose as to whether the MTS impact was relevant to real-world conditions. Problems with the test included the slower than realistic speed of a tine impact, a stroke that was too short to fracture many of the plated end feet, and that the single impact to failure might not be comparable to the actual performance of pallet end feet which could receive many impacts before failure. Further testing with the MTS setup was suspended due to the EG plate curling issue.

B. Inclined-Impact Tester

To more closely simulate realistic conditions, an inclined-impact tester, described in ASTM D-880 [28] was employed. The setup consisted of a four-wheeled dolly on parallel rails inclined at a 10 degree angle from the floor. The dolly was released from a predetermined height on the rails and rolled forward to impact with a stationary forklift tine anchored to a backstop.

ASTM D-1185 [22] describes an impact test for stringer end feet in fully assembled pallets. To test end foot segments, the top of the dolly was modified. This allowed the end foot to be placed top-down on the dolly and supported at the sides and rear to preclude lateral movement at impact (see Figure 3.20).

Figure 3.20 Test Setup for End Feet

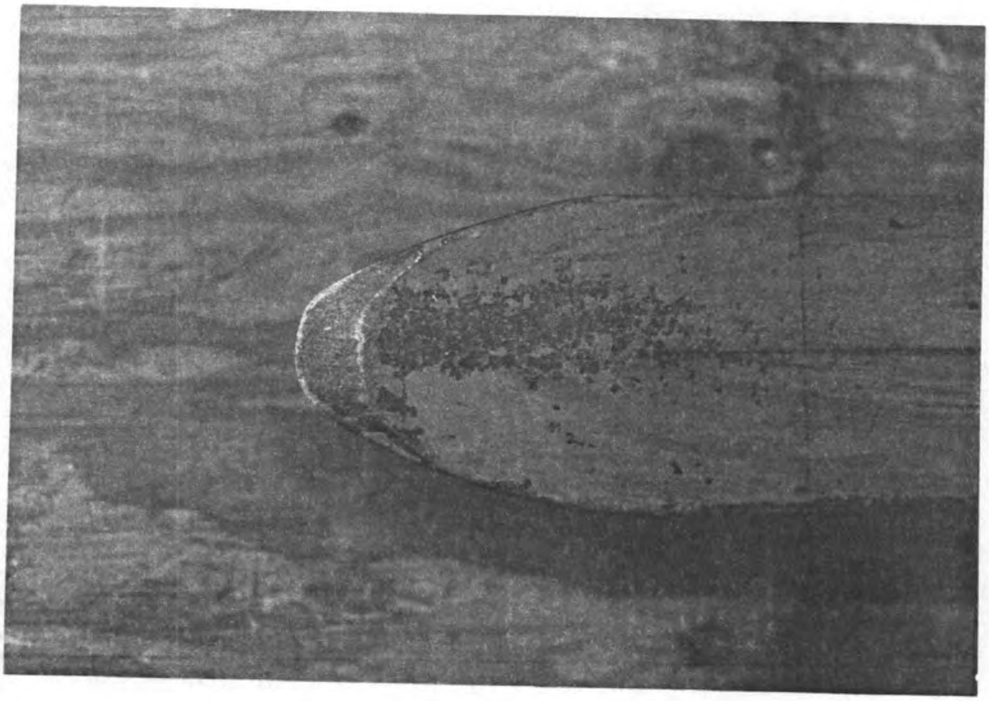

Figure 3.21 Top View of Fork Tine Tip

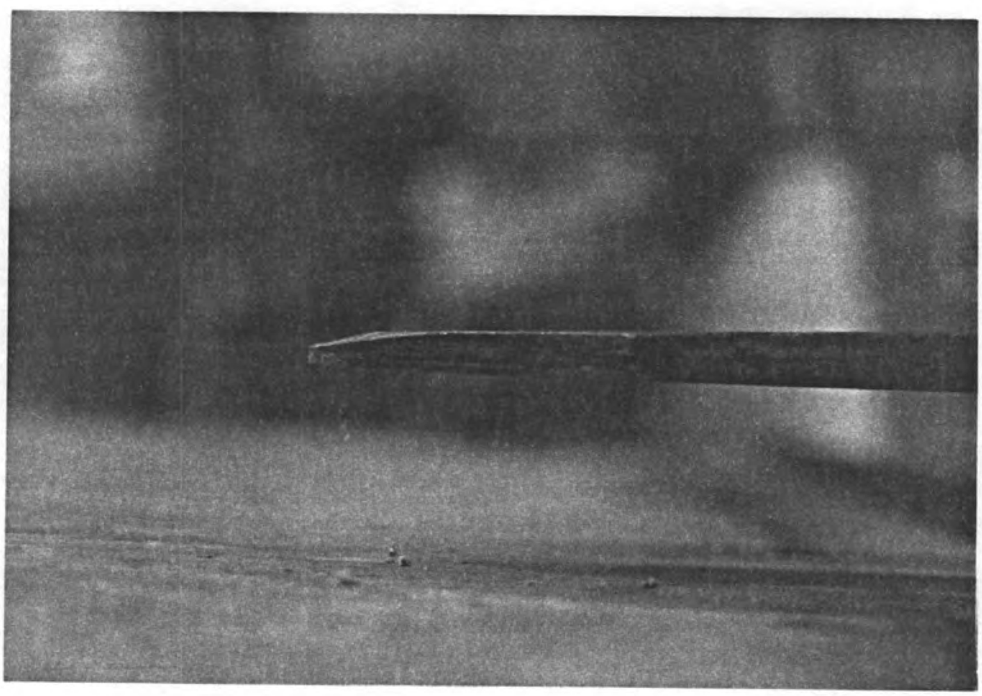

Figure 3.22 Side View of Fork Tine Tip

Impact resistance was defined as the number of impacts required to achieve end foot failure. Failure occurred when the forklift tine split the foot, or when the MCP curled or exhibited tooth withdrawal greater than ¼th inch from the wood surface.

This test setup was used to break both original and repaired end feet. Impact force is related to the mass of the dolly and the distance of dolly travel before impact (Force = mass x velocity^2). The dolly weight box was fixed at 250 lbs. The impact force was adjusted by moving the distance of dolly travel which changed the impact velocity.

Another consideration was the location of the tine impact point on the end foot. The curved tip of the forklift tine (see Figures 3.21,3.22) used in the test made a permanent indentation in the unplated samples during initial testing. In tests of repaired feet, the forklift tine would enter the same indention unless some change was effected. The results could be influenced more by the tine tip than by the plate repair.

Preliminary tests were conducted to determine the optimum distance of dolly travel before impact and whether to impact at the same or a different location on the repaired end foot. Results from initial tests on 1½" wide oak end feet are given in Figure 3.23. End feet were impacted from dolly travel distances of 3, 6, 9, and 12 inches. Retests at each distance for the same and for different points of impact were examined on repaired end feet.

To obtain some variance between samples, multiple impacts prior to failure were necessary, but to complete testing in a reasonable time frame, fewer than twenty impacts to failure were desired. At 9 and 12 inches of dolly travel, a typical, unplated 1½" wide

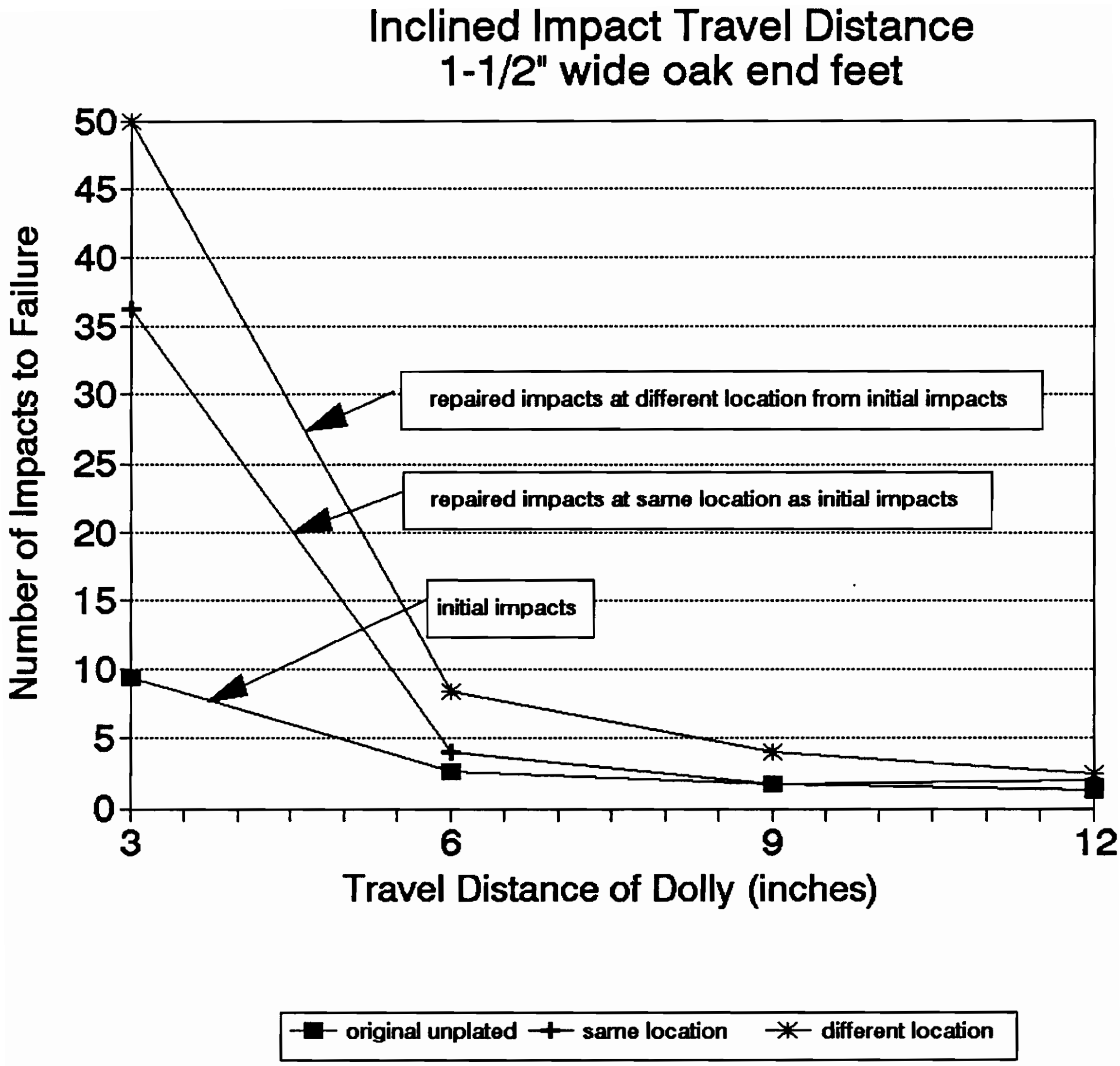

Figure 3.23 Preliminary Tests to Determine Dolly Travel Distance

oak foot failed in 1 or 2 impacts. At 3 inches, a typical repaired oak end foot required an average of 30 impacts to failure. A travel distance of 6 inches was chosen as the best compromise for speed and measurability with both original and repaired end feet.

It was desired to have the same test setup for all species and widths of end feet. A 250 lb. weight and 6 inch travel was the best compromise for 1½" wide oak, 1½" and 2½" wide SYP, and 1½" wide YP stringers. New, unplated 2½" wide oak end feet, however, would not break in 20 impacts at the 6 inch travel and the dolly travel was extended to 12 inches for all tests with 2½" wide oak end feet.

New, unplated end feet and repaired end feet for the same-impact-location tests were impacted 2 inches from the top, at the same height as the notched fillet (see Figure 3.24). The bottom of new, unplated end feet for the different-impact-location tests were placed on a ½-inch tall block (see Figure 3.25), moving the initial point of impact to 2½ inches from the top. Repaired end feet were impacted without the block, 2 inches from the top.

An equal number of impacts to failure were required for both original and MCP-repaired 1½" wide oak feet when tested at the same point of impact and a 6 inch travel. When tested at different points of impact, however, MCP-repaired end feet required 2 to 3 times more blows than the original feet. Because many forklift tines are not pointed at the tip, and there is an unlikely chance that a repaired pallet end foot would be impacted at the exact location of the original failure, the different-impact-location course was selected. The tine impacts on MCP-repaired end feet were located ½" from the tine impacts on original, unplated end feet (see Figure 3.26).

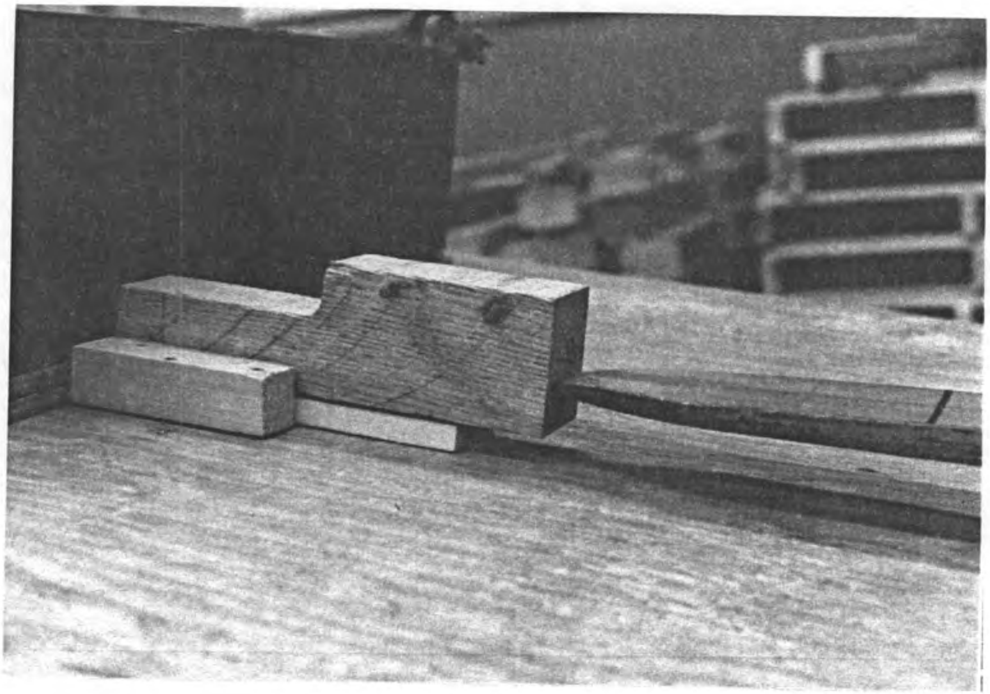

Figure 3.25 **Location of the Initial Point of Impact for the Different-Impact-Location Tests**

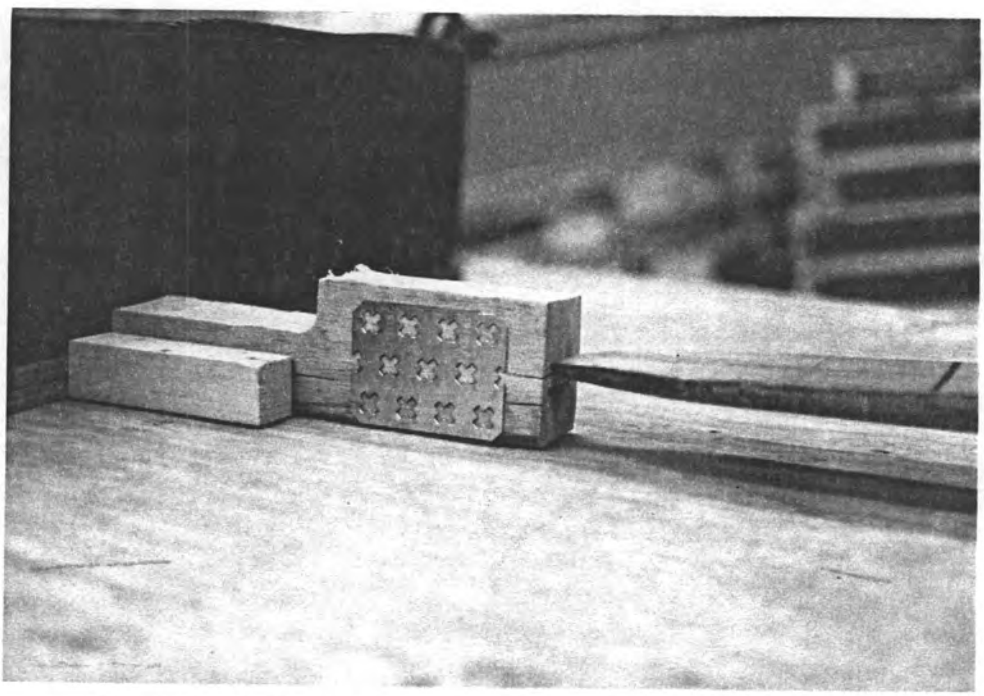

Figure 3.26 **Location of the Second Impact Point for the Different-Impact-Location Tests**

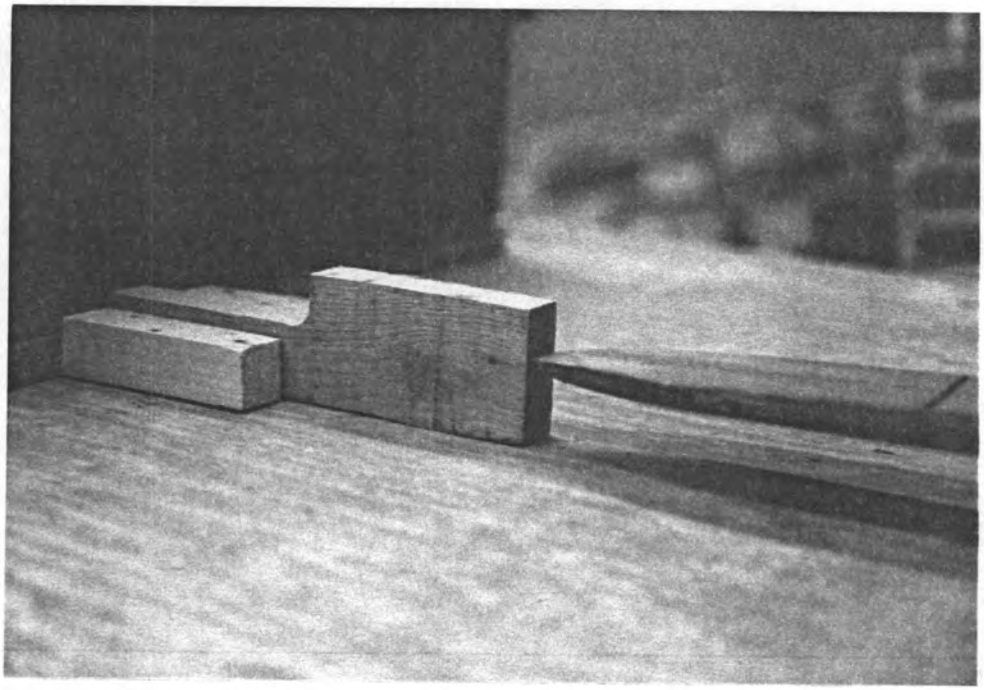

Figure 3.24 Location of the Impact for the Same-Impact-Location Tests

An accelerometer was attached to the dolly to measure the velocity of the sample at the point of impact. The velocity for a travel of 6 inches was 2.2 mph, and at 12 inches was 3.1 mph.

3.6 PALLET TESTS

3.6.1 Experimental Design

RAS (racked-across-stringer) static bending tests and accelerated rough handling tests of full pallets were used for preliminary verification that the results obtained from tests of pallet components also applied to assembled pallets.

A total of 15 pallets were tested. Table 3.6 gives an overview of the experimental design for tests of full pallets.

Reinforcement Performance

Hypothesis: There was no difference in the static bending properties between MCP-reinforced and control pallets.

One MCP-reinforced pallet and one control pallet for each species (oak, SYP, and YP) were subjected to the accelerated rough handling tests. After testing, the RAS static bending performance of the MCP-reinforced and control pallets within each species were compared.

Effect of Pallet Repair Method

Hypothesis: There was no difference in the static bending properties between MCP-repaired, NWPCA Logo-Mark Grade R2, and NWPCA Logo-Mark Grade R3

Table 3.6: Experimental Design - Full Pallet Tests					
	Control	MCP-Reinforced Plate BN1	MCP-Repaired Plates BN1,AN2	Full Stringer Repair	Half Stringer Repair
a. Reinforcement Performance					
oak	1	1	-	-	-
SYP[1]	1	1	-	-	-
YP[1]	1	1	-	-	-
b. Repair Method					
oak	-	-	1	1	1
SYP	-	-	1	1	1
YP	-	-	1	1	1

[1] SYP = southern yellow pine, YP = yellow poplar

repaired pallets.

Grade R2 and Grade R3 Logo-Mark repairs are the traditional methods of pallet repair. Some disadvantages of these traditional methods are price of repair material, reduction in space for tine entry, and weight of the companion members. Grade R2 repairs for two stringers add 8-10 lbs to the weight of a pallet, Grade R3 repairs add 4-5 lbs, but MCP repairs to all inner stringer notches of a three stringer pallet (12 plates) add less than one pound.

This study subset examined whether MCP repairs are equivalent, with respect to RAS strength and stiffness after accelerated handling, to the traditional pallet repair methods. The initial stringer fractures for pallets representing the three repair methods were different, however, and this must be considered in evaluating the results.

Three undamaged pallets for each species (oak, SYP, and YP) were tested to failure in static bending, RAS (racked-across-stringer). All failed due to stringer fractures in the notch areas. One of the three broken pallets, for each species, was repaired with MCPs, one was repaired with companion stringers, and one was repaired with companion half-stringers.

3.6.2 Specimen Selection - Pallets

Because of cost and time limitations, only one pallet was tested for each level of the subset factors, instead of a statistically sufficient sample as with the components. Thus, results from pallet tests are not statistically valid, but provide a preliminary study of MCP performance with pallets.

Five pallets for each of three species (oak, SYP, and YP) were obtained from selected pallet manufacturers in Virginia. One pallet of each species was randomly assigned for MCP-reinforcement and plated while green. One pallet of each species was randomly assigned as an unaltered control pallet. The other three pallets for each species were designated for repair. All pallets were then dried to 12% MC.

The control and MCP-reinforced pallets were nondestructively tested in RAS (racked-across-stringer) static bending to determine initial stiffness. The pallets for repair were tested to failure in RAS static bending to determine initial strength and stiffness.

The intent of the initial tests of pallets for repair was to break two stringers. For all three species, however, pallet failures ranged from two small stringer fractures to major fractures in all three stringers. One pallet for each species was fractured in all three stringers, one pallet of each species had long fractures (8 inches or greater) in two stringers, and one pallet of each species had short fractures (less than 8 inches) in two stringers.

One drawback to companion stringers and half-stringers is the reduction in space for unobstructed forklift tine entry. It is unacceptable to have more than one companion member in an entry opening. If the middle stringer and one outer stringer fail, the companion stringer for the fractured middle stringer is placed on the side away from the fractured outer stringer. A pallet with three broken stringers would not be acceptable for companion stringer repair.

Repair with MCPs, however, does not reduce the size of the entry openings.

Therefore, all pallets with three stringer failures were repaired with MCPs. Pallets having two stringers with long cracks (stringer fracture class IA3 and IA4, Appendix B) were repaired with full stringer companions, pallets having two stringers with short cracks (stringer fracture class IA1 and IA2, Appendix B) were repaired with half stringer companions.

3.6.3 Test Setup - Full Pallet Tests

Oak and yellow poplar (YP) pallets were assembled from green lumber, a typical commercial practice. Southern yellow pine (SYP) pallets were assembled from lumber at 20% MC, as SYP pallet shook is often purchased in the dry condition after rejection from other applications.

The Alpine Mity-Mite plater could not apply MCPs to a full pallet, and a scissors-type pallet plater was used on pallets designed for MCP repair or reinforcement. Reinforced pallets were plated with one pair of MCPs at each stringer inner notch, opposite each other and on both sides of the stringer. There were 4 MCPs per stringer, and 12 MCPs per pallet. The BN1 plate was used for all pallet reinforcement. All pallets were then air dried to approximately 12% MC to maximize possible drying effects.

The number of MCPs used in repair was determined by the interim NWPCA plate-repair guidelines [see Appendix A], which specify one pair of MCPs for fractures under 8 inches long, and two pairs of MCPs for fractures longer than 8 inches. The

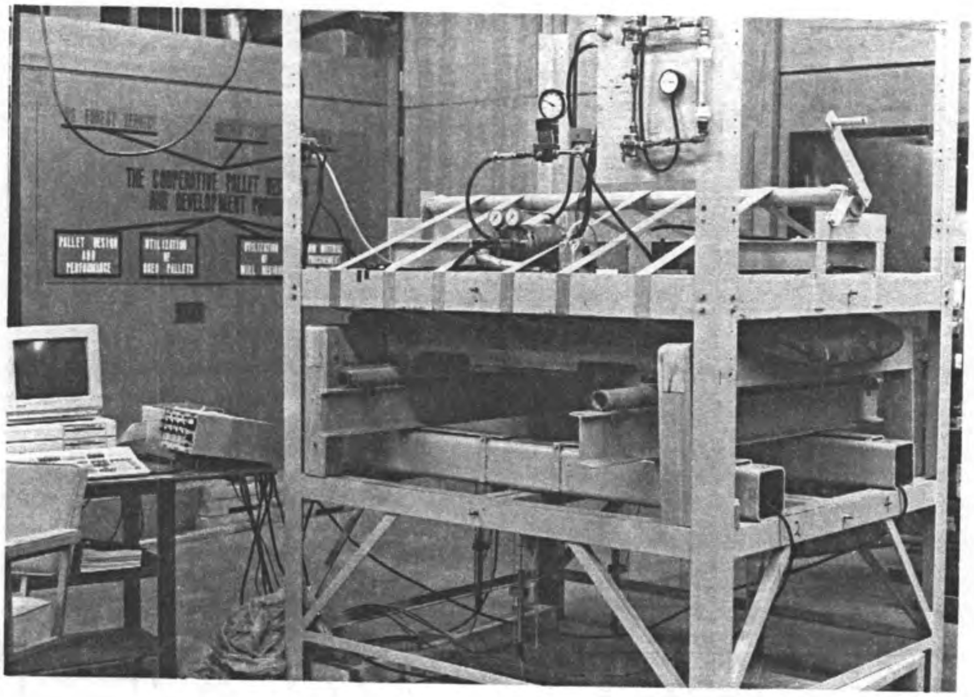

Figure 3.27 Test Setup for Pallet Bending Tests

BN1 plate was used for all between notch fractures. The AN2 plate was used for all above notch fractures. Repair plates were applied to dry pallets.

Other fractured pallets were repaired with wooden companion members following NWPCA guidelines [3]. Both full stringers (NWPCA Logo-Mark R-2 Grade) and half-stringers (NWPCA Logo-Mark R-3 Grade) were used. Companion members were placed adjacent to fractured members and nailed to the deckboards (Philstone brand nails, 2¼" in length, 0.112" in diameter, hardened steel, helically threaded, and diamond point, VPI # 2496).

All static bending tests used the setup and procedures outlined in ASTM D 1185-85 [22], Sections 8-13 (see Figure 3.27). Control pallets and MCP-reinforced pallets were first nondestructively tested in RAS (racked-across-stringer) static bending at 1000 lbs. to determine initial stiffness. These pallets were not damaged during this initial test. Pallets designated for repair were then tested to failure in RAS static bending to determine initial strength and stiffness.

All pallets were then subjected to the VA Tech accelerated material handling test protocol which is outlined in Appendix E.

After rough handling tests, all pallets were tested to failure in RAS static bending, as above, to determine the bending strength and stiffness after simulated use.

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4.0 RESULTS AND DISCUSSION

4.1 OVERVIEW

Research on wooden stringers and pallets with metal connector plates (MCPs or plates) was conducted in two phases. The first focused on repair and the second focused on reinforcement. Both phases included static bending tests and dynamic impact tests. The experimental plan and test setups are given in Chapter 3. The majority of subset hypotheses were evaluated with the performance of pallet components: stringers, notched segments, and end feet. Follow-up tests with full pallets were used to verify the results from component testing.

4.2 PERFORMANCE MEASURES

4.2.1 Repair of Pallet Components

Restoration of original pallet properties by repair may be required if the expected performance of a repaired pallet is the same as that of an undamaged pallet. Pallets not restored to full original properties may still be useful for certain applications, to be determined by the pallet user. Therefore, no specific performance criteria for effective repair of pallet components were set for this study. Effectiveness of plate repairs is given as a repaired performance (RP) percentage, calculated as:

$$R\,P\,(\%) = \frac{Average\ Repaired\ Property}{Average\ Original\ Property} \times 100$$

In this study, the properties evaluated for stringers and notched segments were bending strength and stiffness. The property for end feet was impact resistance, or the number of impacts to failure. If the full original property of a sample was restored, the RP for that property would equal 100% or better. An RP less than 100% means only partial restoration of the property was accomplished.

4.2.2 Reinforcement of Pallet Components

To justify the time and expense of reinforcement, a significant improvement in some property may be needed. As with the repair phase, the properties evaluated for stringers were bending strength and stiffness, and the property for end feet was impact resistance, or the number of impacts to failure. A stringer reinforcement factor, or SRF, was calculated with the following equation:

$$SRF\ (\%) = \frac{Average\ Reinforced\ Property}{Average\ Unreinforced\ Property}\ x\ 100$$

4.2.3 Repair and Reinforcement of Pallets

Several methods (treatments) of pallet repair and reinforcement, and the effect of accelerated material handling on these treatments, were evaluated. Pallets were initially tested in RAS bending, subjected to a simulated 5-year handling test, then retested in RAS bending. Effectiveness of the pallet treatment is given as an accelerated handling performance (AHP) percentage, calculated as:

$$A\,H\,P\,(\%) = \frac{\textit{Pallet Property after Accelerated Handling}}{\textit{Pallet Property before Accelerated Handling}} \times 100$$

The properties evaluated for pallets were RAS strength and stiffness. In this study, the AHP reflects the dual influence of repair or reinforcement and service handling performance. It may be expected that the test pallets would have lower AHP values than the equivalent component RP and SRF values because of the dual effects.

4.3 STATISTICAL METHODS

The Statistical Analysis System, SAS®, [29] on the VA Tech mainframe was used for all statistical analysis. Statistical analysis determined if significant differences existed between treatment groups and within treatment groups.

4.3.1 Between-Group Analysis

Analysis of Variance, ANOVA, tested for significant differences between treatment groups of equal sample size. General Linear Model analysis, GLM, a similar test, was used when sample sizes were unequal. The GLM and ANOVA tests give identical solutions for equal sample sizes. A typical null hypothesis might be that there was no significant difference in a parameter between different treatment groups. The statistic obtained from both the ANOVA and GLM methods was the P-value, which gave the probability that the null hypothesis was true.

Statistics were tested at the 95% confidence level ($\alpha = 0.05$). At this level, a P-value greater than 0.05 indicated no significant difference between the means of the compared groups. A P-value less than or equal to 0.05 indicated a significant difference did exist between at least two of the means of the compared groups.

Between group analysis compared two or more groups. When more than two groups were compared and a significant difference was indicated (P-value $\leq$ 0.05), the Least-Significant-Difference (LSD) comparison method was used to identify dissimilar groups. LSD methods were used to assign groups a letter, beginning with "A". Groups with the same letter were statistically similar.

4.3.2 Within-group analysis

Univariate analysis (paired t-test) was used to make comparisons within a treatment group. Paired t-tests were needed when the compared values were dependent. In the repair phase testing, a sample's performance after repair was influenced by its initial performance (repaired sample dependent upon initial sample). The paired t-test corrected for this dependence during analysis.

In univariate analysis of data from repaired samples, a new variable was formed by subtracting the initial performance of the stringer from that performance after repair. If the difference was equal to zero, then clearly there was no treatment effect. Univariate analysis tested whether the observed variation from zero could have been obtained by chance or was really significant. As with ANOVA and GLM analysis, a 95% confidence interval was used, and the significant difference indicator was a P-value. A univariate P-value greater than 0.05 indicated no significant difference between the original and repaired number of impacts, and a univariate P-value less than or equal to 0.05 indicated there was a significant difference between the two. In the two-tailed test used for the repair phase, a significant difference indicates only that the two means were different. Numeric comparison of the means indicates the relative level of the two.

Within group univariate analysis never compared more than two means. Therefore, no comparison method such as LSD was needed.

4.4 METAL CONNECTOR PLATE REPAIR

The metal connector plate (MCP) repair phase evaluated three types of pallet components: stringers, notched segments, and end feet.

4.4.1 Repair of Stringers

The results from tests of repaired stringers were the static bending strength, static bending stiffness, and the observed failure modes of the repaired stringers. Strength is represented by the maximum bending load of the stringers at failure. Bending stiffness is the slope of the load vs. deflection trace below the proportional limit.

Observed failure modes may give insight into any interaction between plates and stringers. The failure modes from repair testing were influenced by stringer properties,

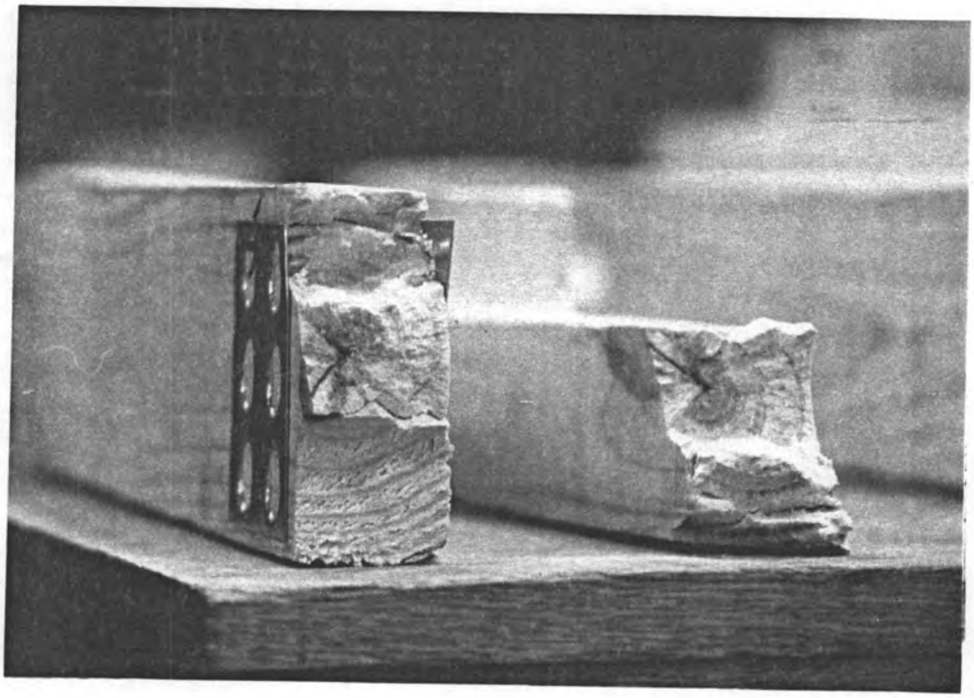

Figure 4.1 Above Notch (AN) Failure Mode in Stringer

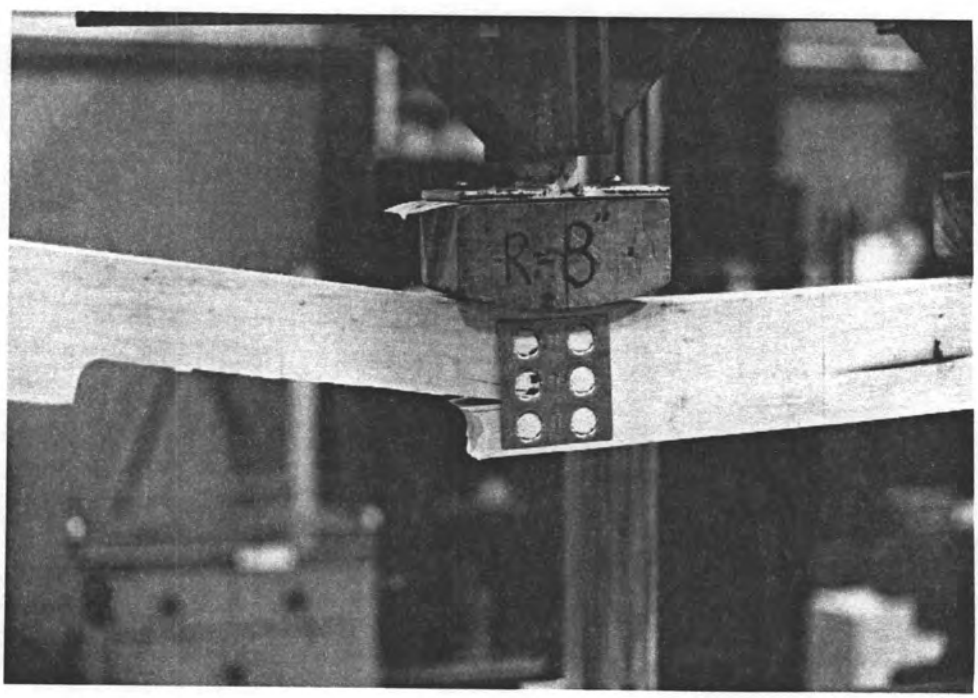

Figure 4.2 Plated Notch (PN) Failure Mode in Stringers

the presence of plates, and the number of plates. While plates were used to mend fractures, they also cut wood fibers when pressed into the wood, reducing the net cross-section of the stringer. Most failures that may be attributed to the presence of MCPs, however, occurred at load levels above those for failure of new, unplated stringers. Typical repaired stringer failure modes are categorized below:

AN failure above a notch, caused by defect in notch area, not a result of plate damage (see Figure 4.1).

PN vertical fractures at a plate between the notches. Caused by plate tooth damage to stringer in between notch area. Predominant failure when plates were used between both stringer notches (see Figure 4.2).

TW plate tooth withdrawal greater than ¼" from the wood surface (see Figure 4.3).

UN failure at unplated notch. Predominant failure when only one pair of repair plates was used (see Figure 4.4).

Effect of Plate Design

Different BN MCPs were applied to each of six groups of fractured 1½" wide oak stringers. ANOVA, shown in Appendix D.1, confirmed that the six groups, before plate application, were statistically similar with respect to width, moisture content, specific gravity, initial strength, and initial stiffness. Table 4.1 shows initial strength and initial stiffness, along with the results of the tests of repaired stringers. The coefficient

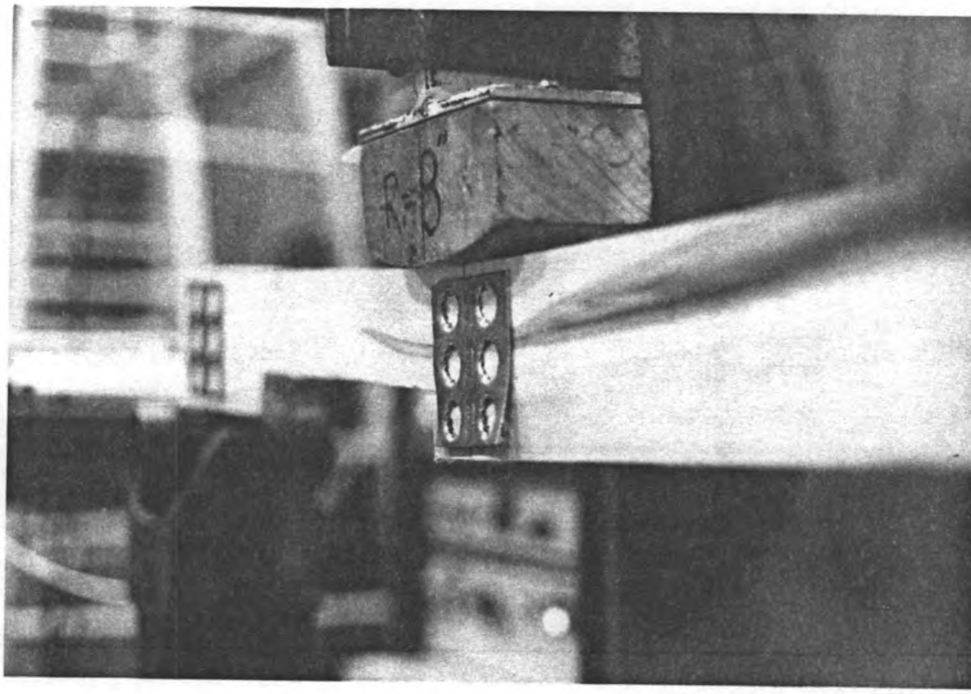

Figure 4.3 Tooth Withdrawal (TW) Failure Mode in Stringer

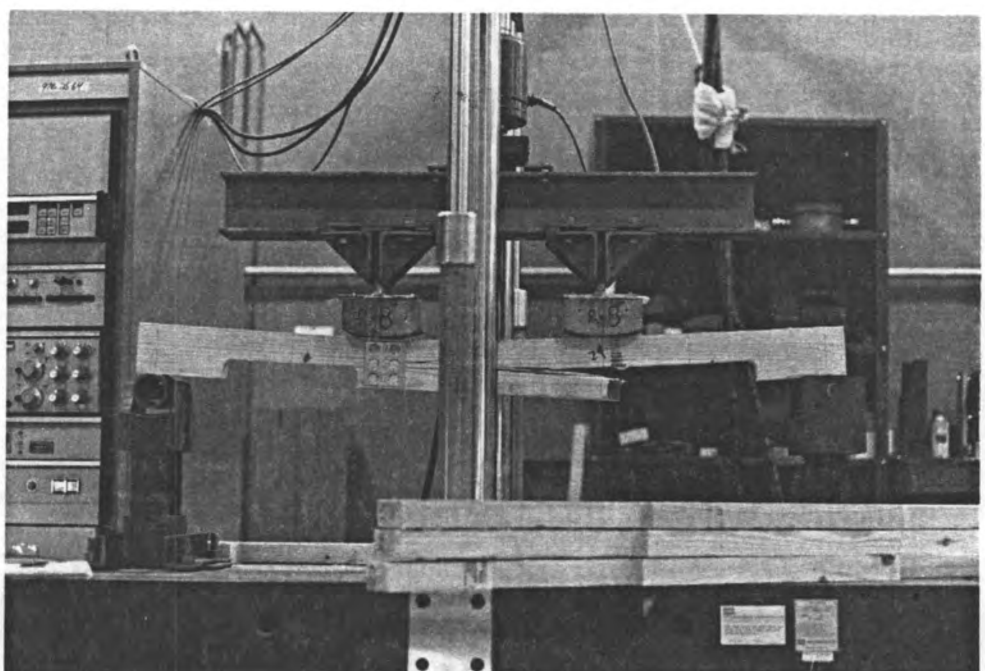

Figure 4.4 Unplated Notch (UN) Failure Mode in Stringer

of variation, COV, is given in the parenthesis to the right of each mean. Repaired performance, RP, means were grouped into "A" or "B" with LSD comparison. Means with the same letter were statistically similar.

Strength: The average maximum strength of the repaired stringers was significantly greater than that of the original stringers for all six plates (Univariate P-values = .0001). That is, the repaired performance, RP, which ranged from 116-127%, was significant. The ANOVA P-value (.4216) indicates that there are no significant differences between the mean strength RP of stringers repaired with the six different plates. The COV is larger for repaired stringer strength than original strength for all plates tested. This reflects a change from one original failure mode (notch fracture) to a variety of failure modes with repair.

Stiffness: The average bending stiffness of repaired stringers was significantly lower than the original stiffness for repairs with all plates except BN3 (Univariate P-value .0828). Strength, however, may be considered a more important quality for repaired stringers than stiffness for many applications.

The ANOVA P-value indicates there was a significant difference between the mean RP for bending stiffness of stringers repaired with the six plates. The LSD comparison indicated that stringers repaired with plate BN3 were stiffer than stringers in groups repaired with the other 5 test plates. The enhanced stiffness of plate BN3 results from its unique, above-the-notch shape. A disadvantage of plate BN3 is that it requires a right-side and a left-side version to plate both sides of a stringer. No other test plate required right-sided or left-sided plates.

Table 4.1: Effect of MCP Design on the Bending Performance of Repaired Notched Oak Stringers

a) Maximum Strength - lbs

Plate Design	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
BN1	1315(7)	1528(16)	.0001	116%	A
BN2	1315(7)	1573(19)	.0001	120%	A
BN3	1313(7)	1668(15)	.0001	127%	A
BN4	1312(7)	1597(23)	.0001	122%	A
BN5	1311(7)	1658(21)	.0001	126%	A
BN6	1310(7)	1605(19)	.0001	123%	A
ANOVA P-value	.9999	-	-	.4216	

b) Stiffness - lbs/in

Plate Design	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
BN1	3023(16)	2626(17)	.0001	87%	B
BN2	3002(13)	2729(15)	.0001	91%	B
BN3	3025(15)	2973(15)	.0828	98%	A
BN4	3073(11)	2760(12)	.0001	90%	B
BN5	3097(15)	2804(20)	.0001	91%	B
BN6	3043(13)	2740(16)	.0004	90%	B
ANOVA P-value	.9266	-	-	.0001	

c) Failure Modes for Repaired Stringers

	AN	PN	TW	UN
BN1	3%	33%	10%	54%
BN2	7%	37%	0	56%
BN3	24%	0	6%	70%
BN4	3%	50%	0	47%
BN5	0	46%	0	54%
BN6	7%	30%	0	63%

Note: numbers in parenthesis are coefficients of variation in percent.

Failure Modes: The majority of repaired stringer failures result from vertical cracks at the plated notch (PN) and between notch cracking at an unplated notch (UN). Few repaired stringers failed from above notch cracks (AN) or tooth withdrawal (TW). An exception was stringers with plate BN3, which was tapered to fit over the notch (see Figure 3.3). The shape of plate BN3 prevented PN-type failures, forcing more AN type failures.

These results mean that a) MCP repair of a stringer fractured at a notch results in a repaired performance for strength which exceeds the original performance, b) all six plates tested were equally efficient at this repair on the basis of bending strength, and c) all groups of stringers had more variation in strength after repair than originally. For stiffness, d) only plate BN3 restores full bending stiffness to repaired stringers, and e) if stiffness is a principal design criteria then MCP repair with the five other test plates may not restore full original performance. Failure mode analysis strongly suggests that improved performance of repaired stringers can be obtained if all interior notches are plated, not just notches at which failures are repaired.

Effect of Mechanical Fracture Closing

Table 4.2 shows the results of the substudy of the two methods of closing a stringer fracture before MCP repair: closing by hand-pressure or mechanically-closing with a piston on the repair machine. Data from the plate design subset were used to represent mechanically-closed fractures. The six treatment groups had statistically similar widths, moisture content, specific gravity, initial strength, and initial stiffness at

Table 4.2: Effect of Fracture Closing Method on the Bending Performance of Repaired Notched Oak Stringers

a) Maximum Strength - lbs

Plate Type and Closing Method		Average Initial	Average Repaired	Univariate P-value	Repaired Performance
BN1	hand	1254(13)	1501(23)	.0001	120%
	mechanical	1315(7)	1528(16)	.0001	116%
	ANOVA P-value	.0776	-	-	.2358
BN4	hand	1250(12)	1691(19)	.0001	135%
	mechanical	1312(7)	1597(23)	.0001	122%
	ANOVA P-value	.0636	-	-	.0419
BN5	hand	1253(11)	1519(21)	.0001	121%
	mechanical	1311(7)	1658(21)	.0001	126%
	ANOVA P-value	.0541	-	-	.3844

b) Stiffness - lbs/in

Plate Type and Closing Method		Average Initial	Average Repaired	Univariate P-value	Repaired Performance
BN1	hand	3163(11)	2849(12)	.0005	90%
	mechanical	3023(16)	2626(17)	.0001	87%
	ANOVA P-value	.2096	-	-	.2940
BN4	hand	3103(17)	2808(14)	.0001	90%
	mechanical	3073(11)	2760(12)	.0001	90%
	ANOVA P-value	.7982	-	-	.8547
BN5	hand	3194(11)	2927(11)	.0001	92%
	mechanical	3097(15)	2804(20)	.0001	91%
	ANOVA P-value	.3825	-	-	.4337

c) Failure Modes for Repaired Stringers

		AN	PN	TW	UN
BN1	hand	0	37%	7%	56%
	mechanical	3%	33%	10%	54%
BN4	hand	9%	30%	9%	52%
	mechanical	3%	50%	0	47%
BN5	hand	13%	33%	0	54%
	mechanical	0	46%	0	54%

the 0.05 level [see Appendix D.3]. Note, however, that for initial strength the similarity between groups may be marginal due to differences between groups of stringers obtained from different mills.

Strength: All groups of repaired stringers had significantly greater mean bending strength than the original stringers, regardless of closing method. ANOVA indicated there was no significant difference between the strength RP of the two closing methods for stringers repaired with plates BN1 and BN5. For plate BN4, however, the strength RP for the group with hand-closed repairs had significantly greater RP than the group with mechanically-closed repairs.

Stiffness: All groups of repaired stringers had significantly less average stiffness than the original stringers, regardless of closing method. ANOVA indicated that there was no significant difference between the stiffness RP of the two closing methods for any of the three plates tested.

Failure Modes: Failure modes for the fracture closing subset do not show a consistent trend with closing method.

These results, which are limited to the methods used and fractures experienced, indicate no significant benefit to mechanically-closing fracture repairs. It should be noted, however, that stringer fractures for this subset were produced in the laboratory, and may not represent field induced stringer fractures. The laboratory produced fractures were relatively straight and free of protruding nails and attached deckboards. Over time, it may be reasonable to expect greater consistency in quality pallet repair and hence, pallet performance, with mechanical closing than with hand closing. This consistency may be more important than the quality of closure achieved by either method.

Effect of Fracture Length

This subset included four treatment groups of 1½" wide oak stringers with four lengths of fractures. All groups were repaired with one pair of type BN1 plates. Significant differences in the bending properties between the groups may indicate the fracture length where use of more than one pair of plates is justified.

ANOVA, shown in Appendix D.2, confirmed that the four treatment groups of 1½" wide oak were statistically similar with respect to width, moisture content, specific gravity, initial strength, and initial stiffness. The results of repaired testing are shown in Table 4.3.

Strength: The univariate P-values indicate that the repaired strength was significantly greater than the initial strength only for the IA1 and IA2 groups. The mean strength of repaired stringers in groups IA3 and IA4 were similar to the original strength of those groups. The ANOVA for strength RP between the fracture classes indicates a significant difference between the means. A LSD comparison indicated that the mean of the samples with fracture type IA1 and IA2 were similar, as were those for types IA3 and IA4. However, groups IA1 and IA2 were significantly stronger than groups IA3 and IA4.

Stiffness: The mean stiffness of all groups was significantly less than that of the original stringers. ANOVA indicates a difference in stiffness RP between the fracture classes. The LSD comparison indicated that the stiffness RP of repaired stringers in fracture

Table 4.3: Effect of Fracture Length on the Bending Performance of Repaired Notched Oak Stringers[1]

a) Maximum Strength - lbs

Initial Fracture Type[2]	Average Initial	Average Repaired	Univariate P-value	Repaired Performance
IA1	1242(19)[3]	1457(22)	.0027	117% A
IA2	1330(20)	1594(20)	.0004	120% A
IA3	1263(21)	1343(23)	.2532	106% B
IA4	1377(22)	1373(21)	.9396	100% B
ANOVA P-value	.2117	-	-	.0357

b) Stiffness - lbs/in

IA1	3046(19)	2708(20)	.0001	89% A
IA2	3113(18)	2759(17)	.0001	89% A
IA3	3033(20)	2584(23)	.0001	85% A
IA4	2969(15)	2088(21)	.0001	70% B
ANOVA P-value	.7915	-	-	.0001

c) Failure Modes for Repaired Stringers

	AN	PN	TW	UN
IA1	4%	18%	0	78%
IA2	7%	3%	0	90%
IA3	5%	9%	11%	75%
IA4	3%	7%	17%	73%

[1] Plate BN1 was used for all repairs.

[2] Fracture length IA1 < ¼ length of middle foot, IA2 < ½ length of middle foot, IA3 < ¾ length of middle foot, and IA4 ≥ ¾ length of middle foot.

[3] numbers in parenthesis are coefficients of variation in percent.

classes IA1,IA2, and IA3 were equal and greater than that of class IA4.

Failure Modes: More than one-half of the repaired stringers in the plate design and fracture closing subsets were repaired with 2 pair of plates, in accordance with NWPCA guidelines [see Appendix A] on fracture length. In this subset, however, only one pair of plates was used per stringer. This difference in the number of notches protected with plates resulted in a large number of UN failures in this subset. Note, as fracture length increased, the percent of TW failures increased. For shorter fractures, the remaining unbroken wood provided some resistance to shear forces. With longer fractures, the repair plates were required to transfer a larger proportion of shear in the beam. In some cases the plate teeth was pulled from the wood.

The results for stringers repaired with one pair of plates mean that: a) the repaired strength of stringers with fracture lengths up to ½ the length of the middle foot was greater than initial strength, b) for fracture lengths over ½ the length of the middle foot, repaired strength equaled initial strength, c) stiffness could not be returned to the original level by repair with a single pair of plates, regardless of the fracture length, and d) repair of stringers with fractures exceeding ¾ the length of the middle foot was less effective, with respect to stiffness, than for the other fracture lengths.

If the principal design criteria is strength, one pair of MCPs at the fracture origin is adequate to restore the original strength, regardless of fracture length. In general, stiffness is not restored to repaired stringers, regardless of fracture length or number of repair plates, but stiffness of stringers repaired with one pair of MCPs decreases as fracture length exceeds ¾ the length of the middle foot. The NWPCA interim repair guidelines [see Appendix A] recommend two pair of MCPs for fractures longer than 8 inches. The study results suggest that this length could be extended to ¾ the length of the middle foot (13.5" in this study; 12" may be a more practical length) before two pair of MCPs are required for fracture repair.

Effect of Species and Width

This subset included two species and two stringer widths. All fractures were repaired with plate BN1. Appendix D.4 compares the strength, stiffness, moisture content, specific gravity, and width of the four treatment groups. Table 4.4 gives the repaired results of the species/width substudy.

Strength: Repaired stringers are significantly stronger than the original stringers for all test species and widths at the 5% level. There is, however, a significant difference between the strength RP of the four groups. A LSD comparison indicates that the strength of 2½" wide oak stringers were more enhanced by repair than the other groups. No consistent width or species effects were evident. Repaired performance of both the SYP and oak groups of 1½" wide stringers were equal.

Stiffness: The stiffness of both groups of repaired oak stringers was significantly lower than the original stiffness. For both widths of repaired SYP stringers, however, the average repaired stringer stiffness was equal to the original stringer stiffness. The stiffness RP for both widths of SYP stringers was significantly greater than the stiffness RP for both widths of oak stringers.

Table 4.4: Effect of Species and Width on the Bending Performance of Repaired Notched Stringers[1]

a) Maximum Strength - lbs

Species and Width	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
1½" oak	1315(7)[2]	1528(16)	.0001	116%	B
2½" oak	1951(21)	2579(23)	.0001	132%	A
1½" SYP	781(25)	916(27)	.0005	117%	B
2½" SYP	1285(21)	1402(25)	.0491	109%	B
ANOVA P-value	-	-	-	.0089	

b) Stiffness - lbs/in

Species and Width	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
1½" oak	3023(16)	2626(17)	.0001	87%	B
2½" oak	4906(13)	3916(16)	.0001	80%	B
1½" SYP	2018(25)	2105(26)	.3381	104%	A
2½" SYP	2876(27)	2879(23)	.9741	100%	A
ANOVA P-value	-	-	-	.0001	

c) Failure Modes for Repaired Stringers

	AN	PN	TW	UN
1½" oak	3%	33%	10%	54%
2½" oak	7%	27%	13%	53%
1½" SYP	5%	45%	10%	40%
2½" SYP	5%	53%	7%	35%

[1] Plate BN1 was used for all repairs.

[2] numbers in parenthesis are coefficients of variation in percent.

Failure Modes: The predominant failures were PN and UN, as with previous substudies. Repaired oak stringers exhibited more UN failures and repaired SYP stringers more PN failures than their counterparts. No consistent effect of width on failure modes was found.

The results mean that a) species differences affect RP values more than width differences, except that there may be a species-width interaction with respect to strength RP, and b) the stiffness of repaired SYP stringers, but not oak stringers, was returned to the original levels.

4.4.2 Repair of Notched Segments

Bending strength of notched segments is represented by the maximum bending load of the segments at failure. Bending stiffness is the slope of the load versus deflection trace below the proportional limit.

Failure modes of repaired segments were also observed to gain insight into any interaction between plates and stringers. The failure modes for repaired segment testing are listed below.

PBUC	plate buckling, compression forces at the top of the plates caused sideways buckling (Figure 4.5).
PBREAK	a tension failure of the plate between a tooth hole and the edge of the plate (Figure 4.6).

TW plate tooth withdrawal greater than ¼" from the wood surface (Figure 4.7).

WOOD the wood portion of the segment failed due to net section reduction caused by plate teeth or to shear along growth rings inside segment (Figure 4.8).

The center-point bending test method for segments was used to consistently create AN-type failures in the initial tests. The stresses developed in the test notch segments, however, may be more extreme than expected in the above notch area of a whole stringer loaded in static bending. In general, the average stringer fails between the notches before bending stress causes an above notch failure.

Consequentially, the notch segment results can be used only for comparative purposes. It is likely that the performance of the repaired segment is secondary to that of the repaired notch. Restoration of a broken AN segment to original levels may not be necessary to achieve a satisfactory level of whole stringer performance. The average stringer repaired above the notch will fail between the notches before the above notch plate repair fails. This concept holds true, however, only for stringers not previously repaired or reinforced at all interior notches.

<u>Effect of Plate Design</u>

Different AN plates were applied to each of five groups of fractured 1½" wide oak segments. ANOVA, shown in Appendix D.5, confirmed that before plate application

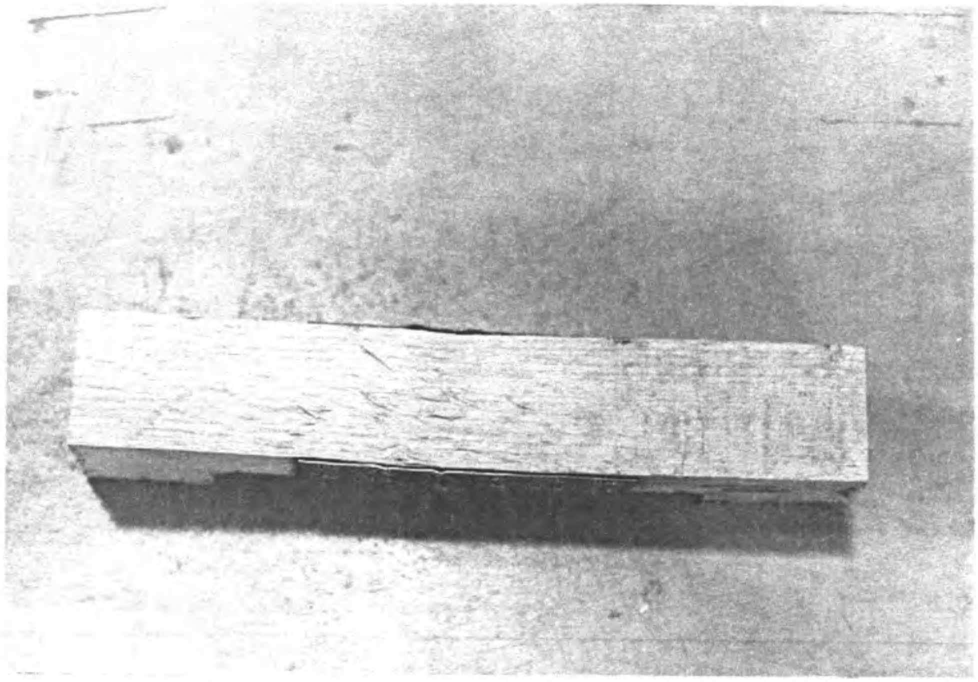

Figure 4.5 Plate Buckling (PBUC) Failure Mode in Notched Segment

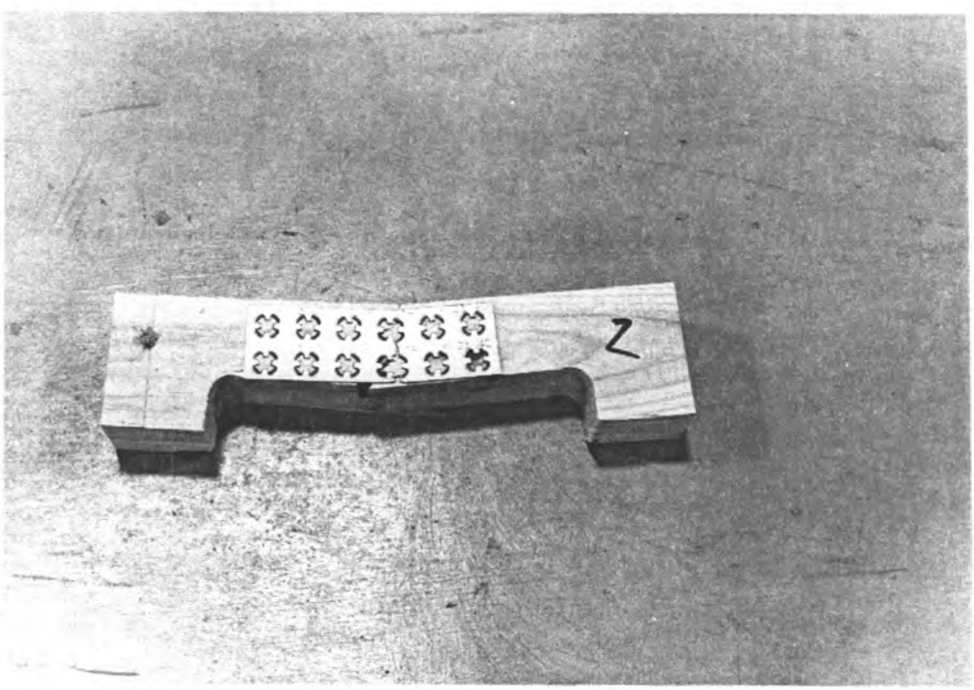

Figure 4.6 Plate Breaking (PBREAK) Failure Mode in Notched Segment

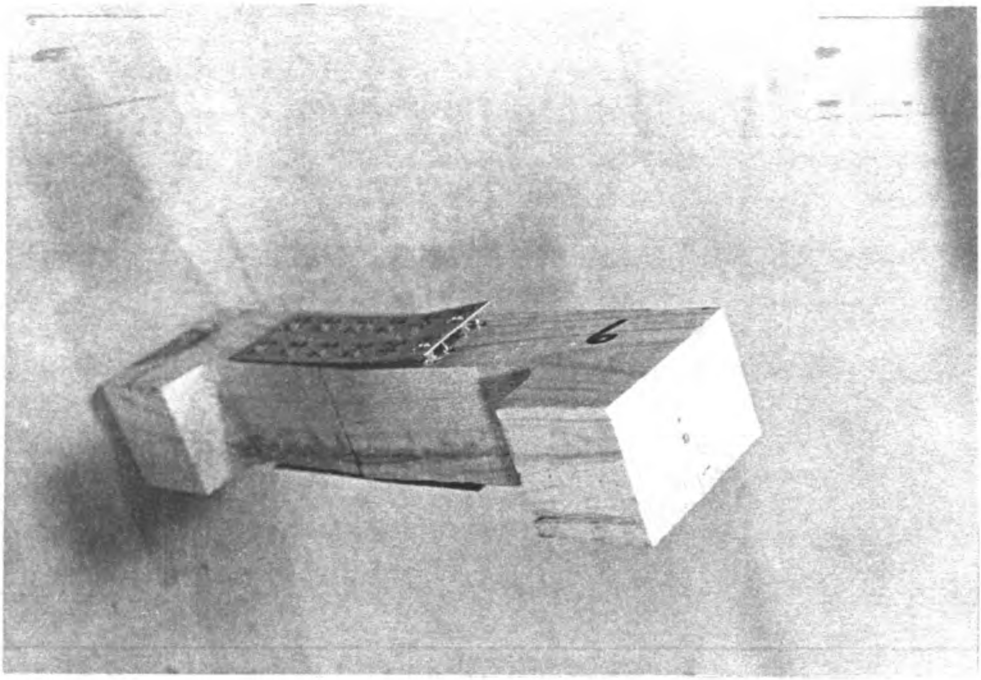

Figure 4.7 Tooth Withdrawal (TW) Failure Mode in Notched Segment

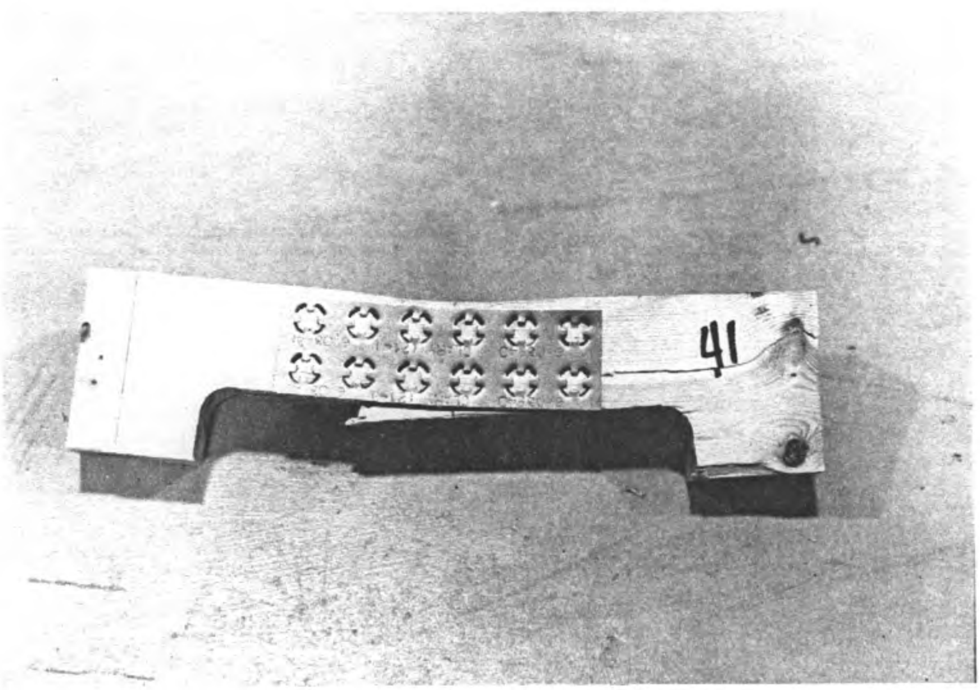

Figure 4.8 Wood Splitting (WOOD) Failure Mode in Notched Segment

the five groups were statistically similar with respect to width, moisture content, specific gravity, initial strength, and initial stiffness. Table 4.5 shows initial strength and initial stiffness and the results of repaired segment testing.

Strength: The average maximum strength of the repaired segments was significantly less than that of the original segments for all five plate designs (univariate P-values .0001). ANOVA indicated that the strength RP for all plates was similar, and in the range of 67-79%.

Stiffness: Only plate AN1 had repaired mean stiffness equal to that of the original stiffness (P-value .1383). ANOVA and the LSD comparison indicate that segments repaired with plate AN2 had significantly less stiffness RP than segments repaired with the other plates. Note that LSD showed that plates AN3, AN4, and AN5 resulted in repaired stiffness similar to plate AN1. The paired t-test is more powerful than LSD and hence one may not conclude that, by inference, the four plates had a stiffness RP equivalent to 100%.

Failure modes: The predominant failure mode for segments repaired with plate AN3 was buckling (PBUC). The primary failure for segments repaired with the remaining plates was plate breaking (PBREAK). Plate AN3, with a notch-surround shape (see Figure 3.9), did not exhibit these breaks but bent in a similar manner as the other plates after buckling.

The results mean that a) MCP repair of a fractured notched segment resulted in average repaired strength performance lower than that of the original segments, b) MCP repair of fractured notched segments results in lower stiffness performance than that of

Table 4.5: Effect of Plate Design on the Bending Performance of Repaired Notched Oak Segments

a) Maximum Strength - lbs

Plate Design	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
AN1	5458(15)	4332(15)	.0001	79%	A
AN2	5550(15)	3714(23)	.0001	67%	A
AN3	5501(16)	3855(22)	.0001	70%	A
AN4	5593(9)	3972(20)	.0001	71%	A
AN5	5613(10)	3960(21)	.0001	71%	A
ANOVA P-value	.9191	-	-	.2091	

b) Stiffness - lbs/in

Plate Design	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
AN1	30074(12)	29079(14)	.1383	97%	A
AN2	30721(17)	26139(17)	.0001	85%	B
AN3	30140(18)	27660(20)	.0220	92%	A
AN4	30245(10)	28904(13)	.0356	96%	A
AN5	30658(8)	28809(14)	.0043	94%	A
ANOVA P-value	.9494	-	-	.0084	

c) Failure Modes for Repaired Segments

	PBUC	PBREAK	TW	WOOD
AN1	20%	43%	21%	16%
AN2	15%	57%	3%	25%
AN3	73%	17%	0	10%
AN4	23%	63%	10%	4%
AN5	22%	71%	0	7%

Note: numbers in parenthesis are coefficients of variation in percent.

the original segments, except for segments repaired with plate AN1 which were equal to their original stiffness, and c) plate AN2 was the least effective test plate for restoring stiffness to notched segments.

The performance required of AN plates for above notch repair of stringers may be less than 100%. This will need to be evaluated on tests of whole stringers with either reinforced or repaired notches as appropriate.

Effect of Fracture Length

This subset included four groups of 1½" wide oak with four lengths of fractures. All groups were repaired with one pair of AN2 plates. ANOVA in Appendix D.6 indicated no significant difference between the four fracture groups with respect to width, moisture content, specific gravity, and initial stiffness. The initial strength of segments, however, decreases as fracture length increases. This suggests that the strength of a notched segment is related to the initial fracture type. Table 4.6 shows the results of repaired testing.

Strength: Notched segment strength after repair was significantly lower than the strength of the original segments for all fracture lengths. ANOVA and the LSD comparison indicate a significant and incremental decrease in strength RP as fracture length increases. It is likely that this decrease of strength in repaired segments reflects the decrease in strength of initial segments as fracture length increases.

Stiffness: Segment stiffness after repair was significantly lower than the stiffness of original segments for all fracture lengths. The ANOVA P-value for stiffness RP,

Table 4.6: Effect of Fracture Length on the Bending Performance of Repaired Notched Oak Segments [1]

a) Maximum Strength - lbs					
Initial Fracture Type[2]	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
IIB1	5954(17)[3]	4743(15)	.0001	80%	A
IIB2	5586(23)	3801(21)	.0001	68%	B
IIB3	5341(21)	3048(23)	.0001	57%	C
IIB4	4953(18)	2329(19)	.0001	47%	D
ANOVA P-value	.0170	-	-	.0001	

b) Stiffness - lbs/in					
IIB1	30332(15)	25590(17)	.0001	84%	A
IIB2	30669(20)	22717(14)	.0001	74%	A
IIB3	30141(13)	23797(12)	.0001	79%	A
IIB4	28275(12)	21279(9)	.0001	75%	A
ANOVA P-value	.5039	-	-	.0841	

c) Failure Modes for Repaired Segments				
	PBUC	PBREAK	TW	WOOD
IIB1	43%	14%	0	43%
IIB2	37%	23%	7%	33%
IIB3	31%	43%	3%	23%
IIB4	12%	77%	0	11%

[1] Plate AN2 was used for all repairs.

[2] Fracture Types IIB1 < ¼ depth of above notch area, IIB2 < ½ depth of above notch area, IIB3 < ¾ depth of above notch area, and IIB4 ≥ ¾ depth of above notch area.

[3] numbers in parenthesis are coefficients of variation in percent.

however, indicates no differences between the fracture lengths at the 5% level.

Failure Modes: As fracture length increased, the percent of PBREAK failures increased and the number of PBUC and WOOD failures decreased. TW was a minor failure mode for all fracture lengths.

The results mean that a) the strength of initial and repaired segments decreased as fracture length increased, b) the stiffness of initial and repaired segments did not decrease as fracture length increased, and c) both the strength and stiffness of repaired notched segments were significantly lower than that of the original segments for all fracture lengths.

The notched segment test gives comparative results only. Additional tests of full stringers with AN fractures are needed to determine if there is a fracture length beyond which AN plate repair is ineffective.

Effect of Species and Width

Segments of two species, oak and SYP, and two widths, 1½" and 2½", were evaluated. Plate AN2 was used for repair of all groups in this subset. The results are given in Table 4.7.

Strength: The bending strength of segments after repair was significantly lower than that of the original segments for all species and widths tested. ANOVA and the LSD comparison show that strength RP was different between the groups. Groups of 1½" wide oak and SYP had similar strength RP, while RP for 2½" wide oak was significantly greater and RP for 2½" wide SYP was significantly lower than the other groups.

Table 4.7: Effect of Species and Width on the Bending Performance of Repaired Notched Oak Segments [1]

a) Maximum Strength - lbs

Group	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
1½" oak	5550(15)[2]	3714(23)	.0001	67%	B
2½" oak	8864(16)	7823(21)	.0013	88%	A
1½" SYP	3042(27)	2007(27)	.0001	66%	B
2½" SYP	4799(18)	2300(24)	.0001	48%	C
ANOVA P-value	-	-	-	.0001	

b) Stiffness - lbs/in

Group	Average Initial	Average Repaired	Univariate P-value	Repaired Performance	
1½" oak	30721(17)	26139(17)	.0001	85%	A
2½" oak	48850(8)	30570(20)	.0001	63%	B C
1½" SYP	16435(19)	11010(19)	.0001	67%	B
2½" SYP	26089(19)	15368(18)	.0001	59%	C
ANOVA P-value	-	-	-	.0001	

c) Failure Modes for Repaired Segments

	PBUC	PBREAK	TW	WOOD
1½" oak	15%	57%	3%	25%
2½" oak	31%	22%	6%	41%
1½" SYP	19%	29%	22%	30%
2½" SYP	2%	27%	31%	40%

[1] Plate AN2 was used for al repairs.

[2] numbers in parenthesis are coefficients of variation in percent.

These results suggest a width-species interaction. Note, however, that initial fractures were longer in the 2½" wide SYP segments.

Stiffness: Repaired segments were significantly more flexible than unbroken segments for all species and widths. There were significant differences between the groups, and the LSD comparison shows that stiffness RP decreased as width increased for both species. The 1½" wide oak segments have a higher stiffness RP than the 1½" wide SYP segments, but 2½" wide oak and SYP segments had equal stiffness RP. There is insufficient evidence to separate the 2½" oak segments into either the "B" or "C" LSD group.

Failure modes: Both groups of repaired SYP segments had more TW failures than the oak groups. As width increased, the percent of wood failures increased for both species.

The results mean that a) there were not consistent differences in segment strength RP between species and widths, b) stiffness RP of segments decreased as width increased for both oak and SYP groups, c) the strength and stiffness of repaired segments was lower than the original properties for all species and widths, and d) a species-width interaction was found for notched segments.

4.4.3 Repair of End Feet

The number of impacts before failure, or the impact resistance, was used to quantify the performance of original and repaired end feet. Observed failure modes may give insight to the interaction of plates and end feet. The typical repaired end foot failure modes are categorized below:

NONE	no failure, testing was halted after 20 impacts on a sample.
CURL	curling of any part of the repair plate more than ¼" from wood surface (Figure 4.9).
TW	tooth withdrawal, occurred when teeth of plate pulled out more than ¼" from the wood surface (Figure 4.10).
WOOD	wood failure, occurred when wood between repair plates split apart and plates remained securely attached to wood (Figure 4.11).

Effect of Plate Design

Plates BN4 and BN5 were each used to repair a treatment group of 1½" wide oak. ANOVA, shown in Appendix D.9, confirmed no significant difference, before plate application, between the two groups for width, moisture content, specific gravity, and initial impact resistance. The results are shown in Table 4.8.

Impact Resistance: The average impact resistance of the repaired end feet for both plates was significantly greater than that of the original end feet. That is, the RP, which ranged from 320-463%, was significant.

Failure Modes: Failure modes show that the true difference in impact resistance between end feet repaired with plates BN4 and BN5 was greater than indicated by the statistical analysis. Due to time constraints, testing of a sample was halted after 20 impacts. Nine BN5 samples did not fail after 20 impacts. If these samples had been tested to failure, the average impact resistance for plate BN5 would have increased, while the average impact resistance for plate BN4 would have remained the same. Plate BN4 was more

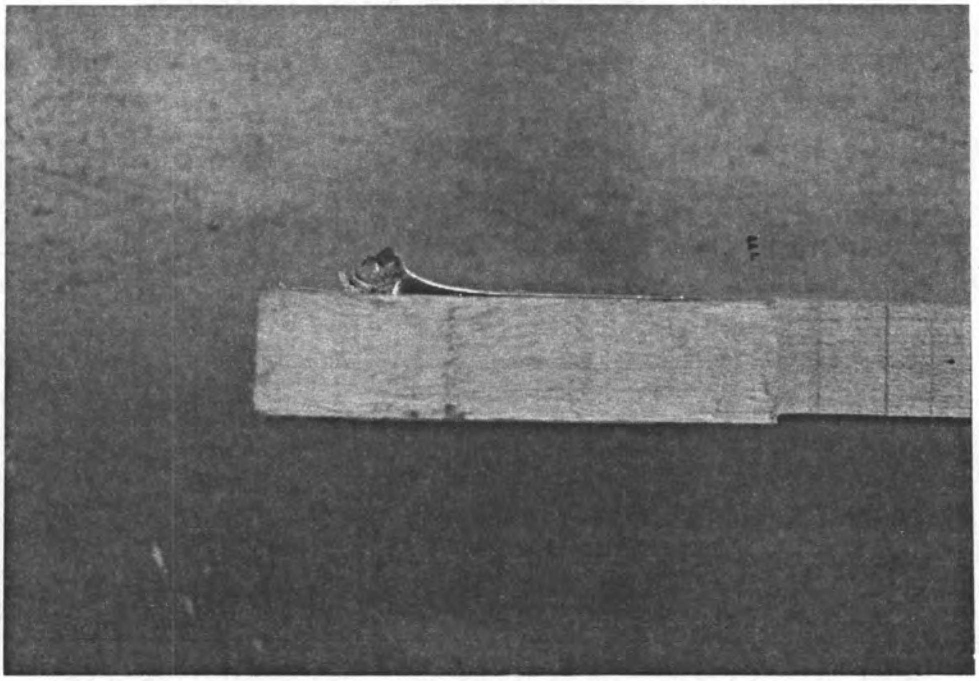

Figure 4.9 Plate Curling (CURL) Failure Mode in End Feet

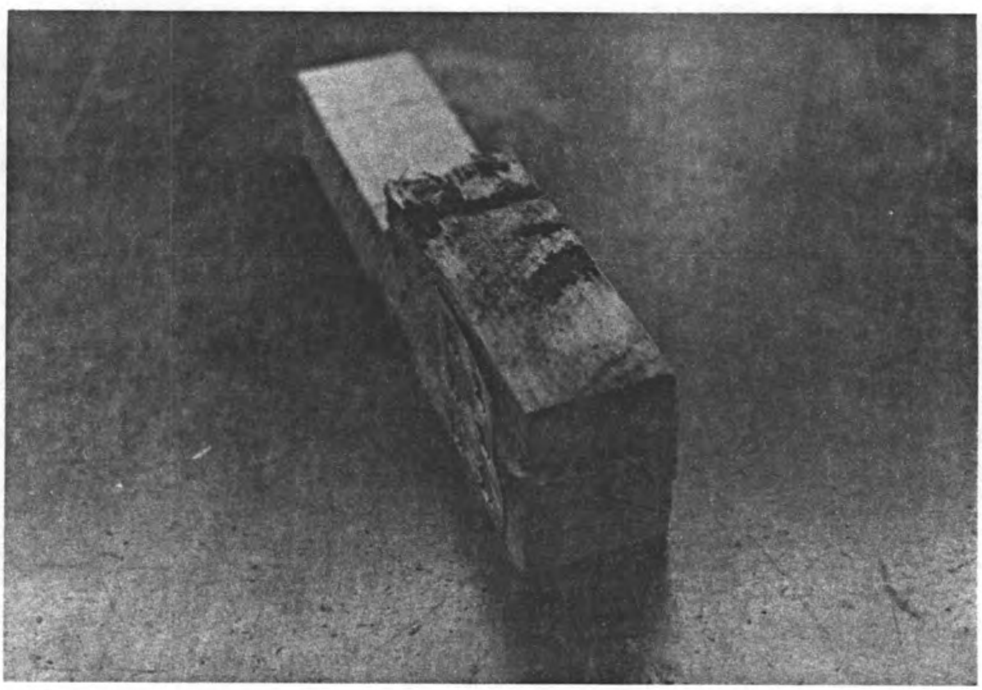

Figure 4.10 Tooth Withdrawal (TW) Failure Mode in End Feet

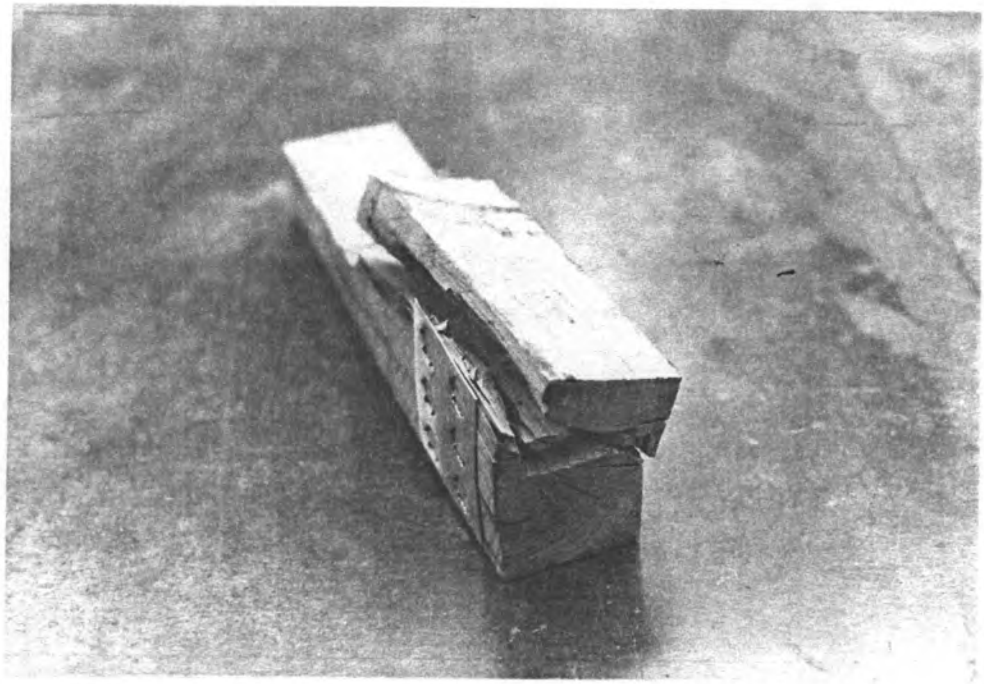

Figure 4.11 Wood Splitting (WOOD) Failure Mode in End Feet

Table 4.8: Effect of Plate Design on the Impact Resistance of Repaired End Feet from Oak Stringers

a) Impact Resistance

Plate Design	Average Number of Impacts Before Repair	Average Number of Impacts After Repair	Univariate P-values	Repaired Performance	
BN4	3.25(30)[1]	10.4(37)	.0001	320%	A[2]
BN5	3.20(31)	14.8(35)	.0001	463%	A
ANOVA P-values	.8735	-	-	.0785	

b) Failure Modes for Repaired End Feet

Plate Design	NONE	CURL	TW	WOOD
BN4	0	55%	0	45%
BN5	45%	25%	0	30%

[1]numbers in parenthesis are coefficients of variation in percent.

[2]Due to the low ANOVA P-value and the large percent of NONE failures for end feet repaired with Plate BN5, it is reasonable to state that end feet plated with BN4 and BN5 are different with respect to impact resistance.

susceptible to MCP curl than plate BN5.

The failure mode results and the low ANOVA P-value suggest that end feet repaired with plate BN5 have a significantly greater impact resistance than end feet repaired with plate BN4. Both plates, however, are likely to be acceptable for end foot repair.

Effect of Fracture Type

This subset included two fracture types, a fracture that split the end foot but left it in one piece [see Appendix B, Class IIIA], and a fracture that split the end foot into two pieces [Class IIIB]. There was no significant difference between the two initial test groups for width, moisture content, specific gravity, or initial impact resistance [see Appendix D.10].

The test setup for repaired end feet in this substudy required tine impacts closer to the top edge than in the plate design subset (Section 3.5.1.A). This resulted in lower repaired impact resistance. The results are shown in Table 4.9.

Impact Resistance: The impact resistance of repaired end feet exceeded the original impact resistance for both types of fractures. No significant difference exists between the impact resistance of end feet with one-piece and two-piece failures.

Failure modes: The predominant failure for both groups was wood splits which resulted from the impact location 1" from the top edge of the end foot after repair. Neither plate BN4, nor any other plate tested in other subsets, was designed to hold the wood together near the edge of the foot, and repeated impacts at the edges will increase wood splitting.

Table 4.9: Effect of Fracture Type on the Impact Resistance of Repaired End Feet from Oak Stringers[1]

a) Impact Resistance

Initial Fracture Type[2]	Average Number of Impacts Before Repair	Average Number of Impacts After Repair	Univariate P-value	Repaired Performance	
IIIA	2.80(32)[3]	3.55(35)	.0001	127%	A
IIIB	2.70(37)	3.80(24)	.0001	141%	A
ANOVA P-values	.7578	-	-	.1646	

b) Failure Modes for Repaired End Feet

Fracture Type	NONE	CURL	TW	WOOD
IIIA	0	20%	0	80%
IIIB	0	45%	0	55%

[1] Plate BN4 was used for all repairs.

[2] Fracture Type IIIA = one-piece end foot fracture, IIIB = two-piece end foot fracture.

[3] numbers in parenthesis are coefficients of variation in percent.

The results mean that a) impact resistance for repaired end feet is lowered as impact location nears the edge of the foot, however the repair is still satisfactory, and b) MCPs, of the type tested, can effectively repair both one-piece and two-piece end foot failures.

The NWPCA interim recommendation against repair of two-piece failures at the end foot area may be overly restrictive if impact resistance is the only criteria. Other practical factors, however, may be more important. Two-piece failures for this study were created in the laboratory with the matching pieces easily pressed together and repaired. If the two-piece failure is not effectively closed, or if one piece is missing and an unmatched piece is substituted, then the performance of two-piece failures may decrease.

Effect of Species and Width

End feet of two species, oak and SYP, and two widths, 1½" and 2½", were tested. Plate BN4 was used for repair.

The results are given in Table 4.10. Note that 2½" wide oak, which was tested at a 12" dolly travel distance, was included for observation only. The 2½" wide oak treatment group was not included in any statistical analysis.

Impact Resistance: The impact resistance of repaired end feet was significantly greater than that of the original end feet for all species and widths. The LSD comparison of the RP values indicates that oak end feet benefit more from MCP repair than SYP end feet, and that 1½" and 2½" wide end feet of each species benefit equally from MCP repair.

Table 4.10: Effect of Species and Width on the Impact Resistance of Repaired End Feet from Stringers[1]

a) Impact Resistance

Group	Average Number of Impacts Before Repair	Average Number of Impacts After Repair	Univariate P-value	Repaired Performance	
1½" oak	3.25(30)[2]	10.4(37)	.0001	320%	A
2½" oak	1.45(35)	4.10(25)	.0001	283%	—[3]
1½" SYP	2.00(28)	3.60(35)	.0001	180%	B
2½" SYP	3.05(36)	4.60(33)	.0001	151%	B
ANOVA P-values	-	-	-	.0089	

b) Failure Modes for Repaired End Feet

Group	NONE	CURL	TW	WOOD
1½" oak	0	55%	0	45%
2½" oak	0	40%	0	60%
1½" SYP	0	10%	20%	70%
2½" SYP	0	15%	10%	75%

[1] Plate BN4 was used for all repairs.

[2] numbers in parenthesis are coefficients of variation in percent.

[3] 2½" wide oak was not included in the statistical analysis.

Failure Modes: The failure modes for both widths of oak end feet were CURL and WOOD. Both SYP species displayed more wood splits and tooth withdrawal than the oak species. Differences in repaired failure modes between widths were minimal.

The results mean that a) oak end feet benefit more from MCP repair than SYP end feet, a result of fewer wood splits and less tooth withdrawal in the oak, b) species determines performance of end feet more than width, and c) all test species and widths of MCP repaired end feet have significantly greater impact resistance than the original end feet.

4.5 METAL CONNECTOR PLATE REINFORCEMENT

The metal connector plate (MCP) reinforcement phase evaluated two types of pallet components, stringers and end feet. Plate BN1 was used for reinforcement of both components.

4.5.1 Reinforcement of Stringers

The typical reinforced stringer failure modes are categorized below:

AN above notch, caused by defect in notch area, not result of plating (see Figure 4.1).

PN vertical fractures at a plate between the notches. Caused by plate tooth damage to stringer in between notch area. Predominant failure when plates were used between both stringer notches, as they were for reinforcement (see Figure 4.2).

TW plate tooth withdrawal greater than ¼" from the wood surface (see Figure 4.3).

Effect of Species and Width

Stringers of three species, oak, SYP, and YP, and two widths, 1½" and 2½", were evaluated. Both reinforced and unreinforced stringers were tested. The average moisture content, specific gravity, and width of the stringers are compared in Appendix D.8. Table 4.11 gives the results of static bending tests.

Strength: The strength of reinforced stringers was significantly greater than that of the unreinforced stringers for all species and widths tested. This met the strength criteria for effective stringer reinforcement. The GLM P-value indicates differences between the SRF values. A LSD comparison shows SYP stringers were enhanced more by MCP reinforcement than the oak or YP stringers, possibly because the initial SYP strength was comparatively low and initial failures were brittle. The 2½" wide oak and 1½" wide YP gained the least from MCP reinforcement. As width increased, the strength SRF stayed the same for SYP, but decreased for oak. The COV values for reinforced stringers were similar to those for unreinforced stringers.

Stiffness: Reinforced stringers had significantly more stiffness than unreinforced stringers for all groups but 2½" wide oak and 1½" wide YP, which had a stiffness equal to the unreinforced counterparts. Both widths of SYP stringers gained more from MCP reinforcement, with respect to stiffness, than the oak or YP. As with strength, the

Table 4.11: Effect of Species and Width on the Bending Performance of Reinforced Notched Oak Stringers[1]

Group	Average Unreinforced	Average Reinforced	ANOVA P-value	SRF	
a) Maximum Strength - lbs					
1½" oak	1315(7)[2]	2286(9)	.0001	174%	B
2½" oak	1951(21)	2416(16)	.0001	124%	C
1½" SYP	781(25)	1540(27)	.0001	197%	A B
2½" SYP	1285(21)	2671(25)	.0001	208%	A
1½" YP	1295(22)	1745(14)	.0001	135%	C
GLM P-value	-	-	-	.0001	
b) Stiffness - lbs/in					
1½" oak	3023(16)	4247(14)	.0001	140%	C
2½" oak	4906(13)	5211(17)	.2096	106%	D
1½" SYP	2018(25)	3795(27)	.0001	188%	B
2½" SYP	2876(27)	6571(20)	.0001	228%	A
1½" YP	3959(12)	3945(14)	.9150	100%	D
GLM P-value	-	-	-	.0001	
c) Failure Modes for Reinforced Stringers					
		AN	PN	TW	
1½" oak		0	97%	3%	
2½" oak		0	93%	7%	
1½" SYP		10%	83%	7%	
2½" SYP		8%	75%	17%	
1½" YP		0	73%	27%	

[1] Plate BN1 was used for all reinforcement.

[2] numbers in parenthesis are coefficients of variation in percent.

stiffness SRF of 2½" oak and 1½" YP gained the least from MCP reinforcement. As width increased, the stiffness SRF increased for SYP but decreased for oak.

Failure modes: The predominant failure for all species was a vertical failure in the stringer under the plate area (PN mode), caused by cuts to the wood fiber from the plate teeth. Stringers that failed in this mode, however, had higher strength than unreinforced stringers. Knots in SYP caused the AN failures. The 1½" wide YP group exhibited more plate tooth withdrawal failures than the other groups, probably due to the lower density of YP compared to the other test species.

The results mean that a) MCP reinforcement of stringers significantly increased bending strength for all species and widths tested, b) SYP stringers benefitted more from MCP reinforcement than oak or YP for both strength and stiffness, possibly because the unreinforced SYP failures were brittle and MCP reinforcement reduced this brittleness, c) a species-width interaction is suggested for both strength and stiffness, and d) when a pair of plates is located between each notch, the predominant failure mode invariably occurs at those plates (PN failure mode).

Species Substitution

The use of MCP-reinforcement to increase utilization of alternate species was investigated. The results are given in Table 4.12.

Strength: The average strength of reinforced 1½" wide SYP and YP stringers was greater than that of 1½" wide unreinforced oak stringers. The variation between reinforced stringers, however, was greater than with the unreinforced oak.

Table 4.12: Species Substitution - Reinforced Notched Stringers (Plate BN1)				
Group	Average Maximum Strength (lbs)		Average Stiffness (lb/in)	
1½" oak - Unreinforced	1315(7)	C	3023(16)	B
1½" SYP - Reinforced	1540(27)	B	3795(27)	A
1½" YP - Reinforced	1745(14)	A	3945(14)	A
GLM P-value	.0001		.0001	

Stiffness: The average stiffness of reinforced SYP and YP stringers was significantly greater than that of unreinforced oak stringers. Stiffness of the SYP group was more variable than the other two groups.

The results mean that with MCP reinforcement, Class B stringers (SYP and YP) could potentially replace Class C stringers (oak) with respect to bending strength and stiffness.

4.5.2 Reinforcement of End Feet

Effect of Species and Width

Treatment groups for 1½" wide oak, SYP, and YP, and 2½" wide oak and SYP were tested. The results are given in Table 4.13. Note that 2½" wide oak, which was tested at a 12" dolly travel distance, was included for observation only. The 2½" wide oak treatment group was not included in the statistical analysis.

Impact Resistance: Impact resistance of reinforced end feet was significantly greater than that of unreinforced end feet for all species and widths tested. There was, however, a significant difference between the SRF values. The impact resistance of 1½" wide oak and YP groups increased more from reinforcement than the 1½" and 2½" wide SYP groups. Differences between widths were small.

Failure Mode: The predominant failure mode for both widths of oak and SYP reinforced end feet was wood splits. The tine used for testing had a rounded point, and when reinforcement plates restricted wood shear splits, the tine impacts split the wood between

Table 4.13: Effect of Species and Width on the Impact Resistance of Reinforced End Feet from Stringers[1]

a) Impact Resistance

Group	Average Number of Impacts Before Repair	Average Number of Impacts After Repair	ANOVA P-values	SRF	
1½" oak	3.25(30)[2]	6.60(37)	.0009	203%	A
2½" oak	1.45(35)	3.15(33)	.0001	217%	—[3]
1½" SYP	2.00(28)	2.80(34)	.0064	140%	B
2½" SYP	3.05(36)	4.10(27)	.0048	134%	B
1½" YP	2.10(26)	4.45(27)	.0001	212%	A
ANOVA P-value	-	-	-	.0092	

b) Failure Modes for Reinforced End Feet

Group	NONE	CURL	TW	WOOD
1½" oak	5%	5%	30%	60%
2½" oak	0	5%	25%	70%
1½" SYP	0	0	30%	70%
2½" SYP	0	5%	20%	75%
1½" YP	0	0	70%	30%

[1] Plate BN1 was used for all reinforcement.
[2] numbers in parenthesis are coefficients of variation in percent.
[3] 2½" wide oak was not included in the statistical analysis.

Table 4.14: Species Substitution - Reinforced End Feet (Plate BN1)

Group	Average Number of Impacts Before Failure	
1-1/2" oak - Unreinforced	3.25(30)	B
1-1/2" SYP - Reinforced	2.80(34)	B
1-1/2" YP - Reinforced	4.45(27)	A
ANOVA P-value	.0001	

the plates. Reinforced YP end feet exhibited more tooth withdrawal. No width differences are apparent.

The results mean that a) the impact resistance of end feet is significantly increased by MCP reinforcement, and b) impact resistance of end feet is more influenced by species than by increasing stringer width.

Species Substitution

The use of MCP-reinforcement to increase utilization of alternate species prone to end foot splits was investigated. The results are given in Table 4.14.

Impact Resistance: The average impact resistance of reinforced YP end feet was greater than the unreinforced oak end feet, while impact resistance of the reinforced SYP end feet was equal to that for the unreinforced oak.

The results mean that, through MCP reinforcement, the impact resistance of Class B species can be increased to that of unreinforced Class C species. This may increase the utilization of these Class B species.

4.6 FULL PALLETS

Tests of whole pallets measured the racked-across-stringer (RAS) static bending strength, RAS static bending stiffness, damage from accelerated handling tests, and failure modes of the plated pallets from RAS bending after accelerated handling. RAS strength is represented by the maximum bending load of the pallet at failure. RAS stiffness is the average slope of the load vs. deflection traces for the three pallet stringers below the proportional limit.

Damage from the accelerated handling tests may give insight to potential problems with the repair and reinforcement methods. Failure modes of plated pallets after accelerated handling may determine pallet areas that need further repair or reinforcement.

The moisture content, specific gravity, and widths of the pallet stringers are given in Appendix D.13.

4.6.1 Accelerated Material Handling of Pallets

Effect of Accelerated Handling:

All fifteen pallets were subjected to a simulated 5-year service handling, consisting of 30 cycles of the VA Tech Accelerated Material Handling Test described in Appendix E. The results are given in Table 4.15.

In general, oak pallets were damaged the least, and SYP pallets the most in the accelerated handling tests. Overall, most damage to pallets was deckboard related (D,R), which was not a focus of this study. Failure D required nails to refasten a deckboard to the stringers, while failure R required a new deckboard (NWPCA Logo-Mark Grade R1 repair) [3]. Much of the deckboard related damage in pallets SYP 1, SYP 2, and SYP 3 occurred in the depalletizing stage. The fork tine attachment used to remove the unit load was too short, causing the lift frame to potentially impact the leading edge deckboard. This was not a commercial depalletizer, and leading-edge deckboard failures rarely occur in the field for this reason. After the tine attachment was lengthened, this deckboard related failure was reduced for the remaining pallets.

Most stringer damage was due to end foot splitting from forklift impacts (E). Typically, this failure required no repair for continued testing, but in some cases additional nails were used to hold the foot together. MCP reinforcement of these end feet may have decreased end foot splits. Many of the end foot splits were two-piece failures, but both pieces remained attached to the deckboards, and it is likely that MCP repair of the end feet would have restored or increased the impact resistance.

The only visual MCP damages (P) occurred in the SYP pallets, and were the result of forklift tines splitting the wood between the plates, not the plates themselves. This was similar to the wood splits found in the plated end foot components. No MCP tooth withdrawal or curling occurred during the accelerated handling tests. More MCP damages would be expected if stringer end feet were plated. Both SYP pallets repaired with companion members, however, experienced end foot splitting in the companion members (C). No single repair method outperformed the others in the accelerated handling tests.

4.6.2 Repair and Reinforcement of Pallets

Effect of MCP Reinforcement

This subset compared unaltered control pallets with MCP reinforced pallets. The pallets were not initially tested to failure, therefore no initial maximum strength values exist. Initial stiffness values were obtained from nondestructive testing. The results are

Table 4.15: Accelerated Material Handling Damage - Pallets

PALLET[1]	CYCLE[2]																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
OAK 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	E	-	-	-	-	-	-	-	-
OAK 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OAK 3	-	E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OAK 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OAK 5	-	-	-	-	-	-	D	-	-	-	-	D	-	-	-	-	-	-	-	-	-	-	-	D	-	-	-	-	-	-
SYP 1	-	-	-	-	-	D	-	-	-	-	-	-	R	-	-	-	-	-	-	-	-	-	-	-	-	D	D	-	-	-
SYP 2	-	D	D	P	R	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SYP 3	-	-	-	-	D	P	-	-	-	D	-	-	-	-	-	-	-	-	-	-	-	R	-	-	-	R	-	-	-	-
SYP 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	C	-	-	-	-	-	-	-	-	-	-
SYP 5	-	-	-	-	-	-	E	-	-	-	-	-	-	E	-	-	-	-	-	D	-	-	-	-	-	-	-	-	-	C
YP 1	-	-	-	-	-	-	-	-	-	-	-	-	D	-	-	D	-	-	E	-	-	R	-	-	-	-	-	-	-	-
YP 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	R	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
YP 3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
YP 4	-	-	-	-	-	E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
YP 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] Pallet Types
1 = Control
2 = Plate-Reinforced
3 = Plate-Repaired
4 = Full-Stringer Repaired
5 = Half-Stringer Repaired

[2] Damage Types
C = companion member end foot damage
D = deckboard damage
E = end foot damage
P = metal connector plate damage
R = deckboard replacement

given in Tables 4.16a, b, and c.

Strength: The RAS bending strength of reinforced pallets after accelerated handling was greater than that of the unreinforced control pallets after accelerated handling for all three species. Species, however, influenced pallet strength more than MCP reinforcement. Tests of stringer components, described in Section 4.5.1, suggest that a reinforced stringer of a low density species may be substituted for an unreinforced higher density species. However, this substitution was not supported by tests of pallets after accelerated handling. The unreinforced oak pallet was stronger than the reinforced YP pallet, and the unreinforced YP pallet was stronger than the reinforced SYP pallet. This suggests that the strength benefits of MCP reinforcement of pallet stringers may decrease with pallet handling.

The MCP reinforced oak and SYP pallets had greater strength, with respect to the control pallets, more than the MCP reinforced YP pallet. This supports the results of MCP-reinforced stringer testing, where strength SRF values were larger for 1-1/2" oak and SYP than for 1-1/2" YP.

Stiffness: The RAS bending stiffness of both reinforced and unreinforced pallets declined after the accelerated handling tests. This was expected, as no additional members or plates were added after the initial stiffness measurements. Although no visual damage occurred to the MCPs during the accelerated handling tests (except SYP), the control pallets had larger accelerated handling performance (AHP) values than the MCP reinforced pallets. This suggests that MCP reinforcement may cause a degrade in stiffness after accelerated handling, possibly due to net section reduction of stringers

Table 4.16(a): Effect of MCP Reinforcement - Maximum Pallet Strength (lbs)		
Species	Treatment	
	Control	MCP-Reinforced
oak	6816	9086
SYP	2598	4223
YP	5091	5316

Note: values represent one replicate pallet only. Plate BN1 was used for all reinforcement.

Table 4.16(b): Effect of MCP Reinforcement - Average Pallet Stiffness (lbs/in)				
Treatment	Species	Before Accelerated Handling	After Accelerated Handling	Accelerated Handling Performance
control	oak	10176	9370	92%
MCP-reinforced	oak	9883	8440	85%
control	SYP	6197	5946	96%
MCP-reinforced	SYP	6908	5974	86%
control	YP	8931	6441	72%
MCP-reinforced	YP	9804	6109	62%

Note: values represent one replicate pallet only. Plate BN1 was used for all reinforcement.

Table 4.16(c): RAS Bending Failure Modes for Reinforced Pallets (Plate BN1)			
Species	AN	NONE	PN
oak	0	33%	67%
SYP	0	33%	67%
YP	33%	33%	33%

Note: Each 33% represents one stringer of a three-stringer pallet. Only one replicate was tested, therefore numbers may not equal 100%.

from plate teeth.

Stiffness AHP for oak and SYP pallets was greater than that for YP pallets. No additional visual damage occurred to the YP pallets, suggesting that the stiffness of YP pallets may suffer more from accelerated handling or the net section reduction from MCPs than oak or SYP pallets.

Failure Modes: Failures in MCP reinforced pallets resembled those in MCP reinforced stringers. The predominant failure mode for all three pallets was PN. A small knot in the YP pallet resulted in one AN failure. One stringer for each pallet did not fail.

These results are limited by the one sample for each species and treatment method. In general, reinforced pallets are stronger than the equivalent control pallet, b) pallet stiffness decreased with handling, with larger decreases in reinforced pallets than with unreinforced pallets, and c) the preponderance of PN failures suggests that additional reinforcement of the stringers is unnecessary to improve static bending strength.

These results are similar to those from reinforced stringer testing. For both pallets and components, strength was increased by MCP-reinforcement more than stiffness, and oak and SYP samples are enhanced more by MCP-reinforcement than were YP samples.

Effect of Repair Method

Three repair methods were used on each of three species of broken pallets. The results are given in Table 4.17.

Table 4.17: Effect of Repair Method on the Bending Performance of Pallets[1]

a) Maximum Pallet Bending Strength (lbs)

Repair Treatment	Species	Initial	After Repair and Accelerated Handling	Accelerated Handling Performance
MCP	oak	4878	5109	105%
Stringer	oak	5423	10222	188%
Half-Stringer	oak	4847	7392	153%
MCP	SYP	2553	2332	91%
Stringer	SYP	3222	3441	107%
Half-Stringer	SYP	3706	3170	86%
MCP	YP	3131	3701	118%
Stringer	YP	4427	6464	146%
Half-Stringer	YP	2597	4729	182%

b) Pallet Stiffness (lbs/in)

Repair Treatment	Species	Initial	After Repair and Accelerated Handling	Accelerated Handling Performance
MCP	oak	9989	4017	40%
Stringer	oak	10910	7531	69%
Half-Stringer	oak	10412	9805	94%
MCP	SYP	5188	3259	63%
Stringer	SYP	9246	9097	98%
Half-Stringer	SYP	7765	5660	73%
MCP	YP	7628	5665	74%
Stringer	YP	9554	10995	115%
Half-Stringer	YP	8997	7656	85%

c) Bending Failure Modes for MCP Repaired Pallet Stringers[2]

	AN	NONE	PN	TW	UN
MCP-repaired oak	0	33%	0	67%	0
MCP-repaired SYP	33%	0	67%	0	0
MCP-repaired YP	0	33%	0	33%	33%

[1] Plate BN1 was used for all MCP repairs.

[2] values represent one replicate pallet only. Each 33% failure represents one stringer of a three-stringer pallet. Numbers may not equal 100%.

Strength: For oak and YP pallets, RAS bending strength after accelerated handling was greater than that of the original pallets for all three repair methods. For SYP pallets, only the full companion repair was stronger after accelerated handling than originally. Strength AHP values for oak and YP repair methods were greater than those for SYP, suggesting that, with respect to strength, repair overall is less effective for SYP, and/or SYP pallets were affected more by the accelerated handling tests than the oak and YP pallets.

For oak and SYP pallets, full companion repair (Grade R2) had the largest AHP values. The half stringer repair of the YP pallets resulted in the largest AHP. The MCP-repaired pallets had the lowest strength AHP values for oak and YP. Remember, however, that the MCP-repaired pallets initially had all three stringers fractured, while the companion member pallets had only two initial stringer fractures (Section 3.6.2). These differences and the limited sample size precludes any further conclusions.

Stiffness: The RAS bending stiffness for all three repair methods declined after accelerated handling, except for the YP full companion repair pallet. The addition of the two YP repair stringers made this pallet stiffer than any other pallet, regardless of species or treatment. Of the three repair methods for each species, the MCP repaired pallet had the lowest stiffness AHP values. The full stringer repairs had the largest AHP for SYP and YP, but the half-stringer repair had the largest stiffness AHP for oak.

Failure Modes: Failures in MCP repaired pallets resembled those in MCP repaired stringers, except that splits along the middle foot would stop at a deckboard nail. No deckboard nails were used in the component tests. The most common failure for SYP pallets was PN, while TW was more common with the oak pallet. The increase in TW failures, and decline in UN failures, as compared with component stringers, may reflect a difference in the quality of whole pallet repair as compared to stringer repair in the laboratory. The one stringer with the AN plate repair (YP pallet) failed at the opposite notch (UN failure). This was the only UN failure, and suggests that AN plates may be effective for pallet repair.

These results of pallet testing are limited by having only one replicate for each species and repair method, and by the fact that initial failures in all pallets were not similar. In general, the results suggest that a) all repair methods restore original strength in oak and YP pallets with MCP repair being less effective than full companion stringer repair, and b) strength is more easily restored to pallets by repair than is stiffness.

The AHP values for pallets are lower than the equivalent RP values for stringer components. This may reflect the effect of accelerated handling and/or a different quality in whole pallet repair than laboratory repair of components.

4.7 APPLICATION OF RESULTS

In 1991, the National Wooden Pallet and Container Association, NWPCA, published Guidelines for the Use of Pallet Metal Connector Plates [see Appendix A], based on the best information available at the time regarding the successful use of pallet plates.

This thesis addressed many of the recommendations of the NWPCA and are discussed below. To aid location of the recommendation, the paragraph reference number from the guidelines in Appendix A is given in parenthesis.

REPAIR

(1) *"The longest side of the plate should always be placed horizontally along the break."*
Plate BN1, measuring 2¾" x 3", was designed for the shorter side of the plate to be placed horizontally along a break. Strength and stiffness performance of stringers plated with BN1 was comparable to stringers with the other BN plates. All other BN plates did have the longest side horizontal to the break. The rationale for this requirement is not directly supported by study results.

(1) *"Horizontal breaks greater than eight (8) inches in length occurring between the notches should be repaired with four plates."*
For between notch failures in stringers, only one pair of plates, regardless of fracture length, was required to restore strength to the original level. The stiffness of repaired stringers, however, could not be restored to the original level with one pair of plates for any fracture length. Further decline of stiffness occurs as fracture length exceeds ¾ the length of the middle foot (13.5" in this study). The study results suggest that the 8 inch restriction for one pair of plates could be extended to 12 inches.

(2) *"The break should be pressed closed mechanically, hydraulically, or pneumatically, prior to application of the plate."*

No increase in stringer strength or stiffness was found when fractures were mechanically closed before plate repair. Test stringer fractures were produced in the laboratory, however, and were free of nails and connected members. Greater consistency in repaired component performance may be expected by mechanically closing stringers fractured in service. The decision to eliminate the requirement for mechanical fracture closing will need to be supported with tests of pallets broken in service.

(9) *"Do not plate (connect) two or more pieces of stringer together to replace, or add to, an existing stringer."*

No difference in impact resistance was found between one-piece and two-piece end foot failures. Two-piece failures were created in the laboratory, however, and matching pieces were easily pressed together and repaired. If pieces are missing or not pressed together, the performance of two-piece fractures may decrease. It is recommended that two-piece fracture repairs be permitted if all pieces are present and the fractured surfaces can be mated.

REINFORCEMENT

(2) *"End plating/capping on the end of the stringer may also be done for additional stringer protection to minimize damage to the ends of stringers resulting from the impact of forktruck tines."*

Preliminary impact tests of end feet reinforced with end grain plates indicate that most failed by plate curl (greater than ¼ inch) before wood failure. More research is needed to determine if end grain plates offer a practical method of end foot reinforcement.

4.8 RECOMMENDATIONS FOR FUTURE RESEARCH

The RP values found in this study may be overstated, since failure was cleanly introduced before repair. A better measure of the RP would be to measure the strength of repaired and unbroken used stringers sampled from the field. Laboratory tests, however, do give an effective way to assess the relative effects of MCP repair using different plate installation practices, etc.

Stringers fractured above the notch and repaired with AN plates are needed to determine the effectiveness of the AN plates. The test method used in this research merely gave a comparison between the AN plates.

Preliminary pallet testing supports many of the component results, but further investigation of MCP performance with pallets would be needed to confirm that component testing provides an effective method of predicting pallet performance.

The current pallet industry standard for the thickness of MCP steel is 20 gauge (0.034 inch). Various manufacturers have expressed interest in the use of thinner plates for pallet repair. Our results indicate that repaired components (excluding notched segments) were stronger than the original components, suggesting that plate performance may be better than required. Less expensive plates might be manufactured from thinner steel, while maintaining the same net cross-section of the plate. Possible disadvantages of thinner plates are increased difficulty in quality installation of plates due to tooth bending, and uncertain economics of thinner plates as compared to the MCP industry-standard 20 gauge steel produced in bulk quantity.

This study did not evaluate plate gauge as a variable. Extrapolation of these results to thinner plates should not be done because of potential changes in failure modes.

The straightness of repaired stringers in the field is inherently less than that of new, undamaged stringers. The ability of plate repairs to restore straightness would need to be evaluated with tests of fractured stringers obtained from used pallets.

5.0 SUMMARY AND CONCLUSIONS

If properly applied, metal connector plates (MCPs) can effectively restore pallet strength, but not stiffness. Reinforcement of pallet stringer notches and end feet provides positive benefits and may allow the use of less desirable species in quality pallets. No consistent interaction of test species (oak, SYP, and YP) and test stringer widths (1½" and 2½") were found for bending strength or bending stiffness on plated notched stringers and notched stringer segments. Specific conclusions are as follows:

5.1 BETWEEN NOTCH MCP REPAIR OF STRINGERS

a) The average third-point bending strength of MCP repaired stringers was greater than that of the original stringers for the six plate designs tested.

b) There were no significant differences between the strength repaired performance (RP) of the six plates.

c) In general, MCP repair could not restore original stringer stiffness.

d) One pair of MCPs is recommended for fractures up to ¾ the length of the middle foot (13.5 inches); two pair of MCPs are needed for longer fractures.

5.2 ABOVE NOTCH MCP REPAIR OF NOTCHED SEGMENTS

a) The test method required to create above notch (AN) fractures was not representative of field loading of pallets and consequentially, notched segment test results may be used only for comparative purposes.

b) In general, MCP repair could not restore original segment strength or stiffness.

c) There were no significant differences between the strength RP of the test plates.

d) A decline in bending strength was found for both original and repaired segments as fracture length increased.

e) The stiffness of repaired segments remained the same as fracture length increased.

5.3 MCP REPAIR OF END FEET

a) Repaired end feet had a greater impact resistance than the original undamaged end feet.

b) Wood species had a more significant effect than stringer width on MCP repair performance.

c) There was no difference between impact resistance of one-piece and two-piece end foot fractures. However, this result applies only to repairs where original pieces are joined with fracture surfaces correctly mated.

5.4 BETWEEN NOTCH MCP REINFORCEMENT OF STRINGERS

a) The average reinforced bending strength of stringers was greater than the average unreinforced bending strength for all species and widths tested.

b) The stiffness of reinforced stringers was greater than or equal to unreinforced stiffness.

5.5 MCP REINFORCEMENT OF END FEET

a) Reinforced end feet had greater impact resistance than unreinforced end feet for all species and widths tested.

b) Wood species was a better indicator of MCP reinforcement performance than stringer width.

5.6 PALLETS

a) In general, the results of pallet testing support the conclusions from stringer and end foot component testing. The test setup for notched segments, however, may not adequately represent pallet performance.

b) Bending strength of pallets may be restored by repairing pallet stringers, but bending stiffness is not.

c) Full companion stringer repair was more efficient than MCP repair in terms of bending strength, but both methods generally restore bending strength to their original levels. MCP repaired pallets were fractured in all three stringers, however, while full companion stringer pallets had only two fractured stringers. MCP repair may be more attractive than full stringer repair because of lower weight and no reduction of space for tine entry.

d) MCP reinforcement increased pallet strength and decreased pallet stiffness for all three species. Differences between species were inconsistent for the repair methods.

5.7 TEST METHODS

a) The test method for stringers fairly represents the performance of pallet stringers in bending.

b) The test method for stringer end foot impact resistance is convenient, practical, and cost-effective. It does allow for differentiation between study variables. There is, at present, no established correlation between tested impact resistance and in-service performance. It is reasonable, however, to expect that any major differences between the study variables found in the laboratory will also be seen in the field.

c) The test method used to assess above notch fracture repairs in notched segments does not represent the effects of field loading on pallets. Further testing of above notch repair may be better represented with tests of whole stringers fractured above the notch.

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APPENDIX A

GUIDELINES FOR THE USE OF PALLET (Metal Connector) PLATES

The following voluntary guidelines are based on the best information currently available regarding the successful use of pallet (metal connector) plates. The National Wooden Pallet and Container Association (NWPCA), is currently conducting research which will provide specific guidance on how best to utilize pallet (metal connector) plates for pallet stringer repair and for the reinforcement of stringers in new pallets. The research will also determine whether the size of the plate impacts on the performance of the pallet.

DESCRIPTION OF THE PALLET (METAL CONNECTOR) PLATE:

Pallet (metal connector) plates should be made from 20 gauge commercial grade, galvanized steel with a minimum thickness of .034 inches and a minimum of 4 punched teeth per square inch.

USE FOR STRINGER REPAIR:

1. Two plates per repair should be used. Plates should be applied opposite one another on each side of the stringer, and mechanically, hydraulically or pneumatically pressed flush into the wood. The length of the plate, if greater than the width, should always be placed horizontally along the break. Horizontal breaks greater than eight (8) inches in length occurring between the notches should be repaired with four plates,(i.e., two plates at each end of the break and opposite each other on both sides of the stringer).

2. Repair horizontal or diagonal breaks only, not vertical. The break should be pressed closed mechanically, hydraulically or pneumatically, prior to application of the plate. The teeth of the plate must be pressed into the wood on both sides of the stringer so that the plate is flush with the wood. Breaks at large knots (1" or larger) are not eligible for plate repair.

3. Align plates properly with the stringer. Failing to do this will result in overhang of the plate on the end, top or bottom of the stringer. Plate overhang may cause product damage or the inability for the pallet to move through automated material handling systems.

4. Apply plates only with machinery designed and manufactured to do so by means of mechanical, hydraulic or pneumatic power so that the plate is flush with the wood. Never apply plates by hand or by using a hammer.

5. Do not plate breaks above the notch or where a portion of the stringer is missing.

6. Do not repair the damaged or split end of a stringer by end-plating or capping.

7. Do not repair broken blocks or broken deckboards by plating. They should be replaced.

8. Do not reduce the original plate size by cutting the plate into any smaller dimension.

9. Do not plate (connect) two or more pieces of stringer together to replace, or add to, an existing stringer.

(For the purpose of these guidelines, the term "break" and "crack" are synonymous.)

USE ON NEW PALLET STRINGERS

1. Pallet (metal connector) plates may also be used to reinforce new pallet stringers. Plates applied for reinforcement should follow the guidelines described above for stringer repair.

2. End plating/capping on the end of the stringer may also be done for additional stringer protection to minimize damage to the ends of stringers resulting from the impact of forktruck tines.

NATIONAL WOODEN PALLET AND CONTAINER ASSOCIATION
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DO'S AND DON'TS IN PALLET PLATING

Do's

1. **Do plate horizontal or diagonal breaks on the vertical face of the stringer where the plate can grip above and below the break.** (Figure 1a-d).
2. **Do use two (2) plates per repair** applied opposite one another on each side of the stringer.
3. **Do apply plates** only with machinery designed and manufactured to do so by means of mechanical, hydraulic or pneumatic power so that the teeth are fully pressed into the wood and the plate is flush with the wood.
4. **Do use four (4) plates** for breaks greater than eight (8) inches (i.e., two plates at each end of break and opposite each other on both sides of the stringer.) (Figure 2).
5. **Do press break closed** with mechanical, hydraulic or pneumatic power prior to plate application.
6. **Do align plates** properly with stringer to prevent plate overhang.

Don'ts

1. Don't plate a vertical break through the center of the stringer. (Figure 3).
2. Don't plate breaks on the side of the stringer running through the top of the stringer. (Figure 4).
3. Don't plate where a portion of the stringer is missing. (Figure 5).
4. Don't plate breaks above the notch. (Figure 6).
5. Don't repair the damaged or split end of a stringer by end-plating or capping.
6. Don't repair broken blocks or broken deckboards by plating. They should be replaced.
7. Don't reduce the original plate size by cutting the plate into any smaller dimension.
8. Don't plate (connect) two or more pieces of stringer together to replace, or add to, an existing stringer.
9. Don't plate breaks at knots one (1) inch or larger.
10. Don't apply plates by hand or by using a hammer.

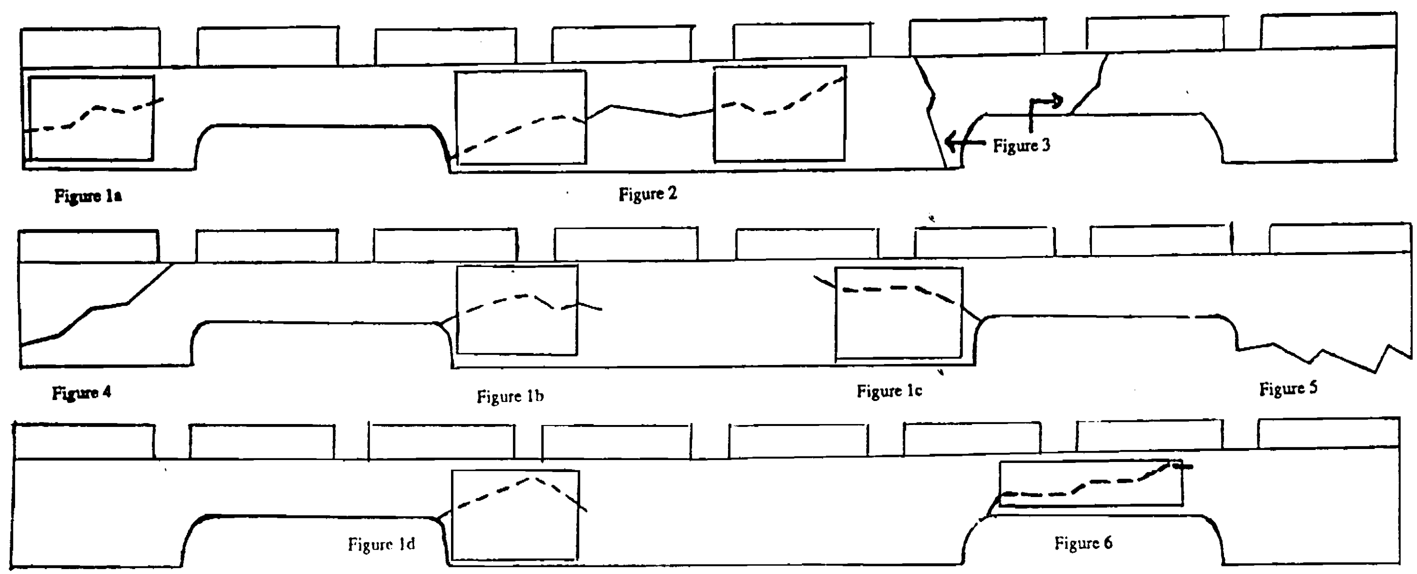


Figure 1a; Figure 2; Figure 3

Figure 4; Figure 1b; Figure 1c; Figure 5

Figure 1d; Figure 6

APPENDIX B

REPAIR FAILURE CLASSIFICATION

CLASS I. Between Notch (BN) Static Bending

A. Straight Fracture (slope 1" in 5" or less)
1. < 1/4 length of middle foot
2. between 1/4 and 1/2 length of foot
3. between 1/2 and 3/4 length of foot
4. > 3/4 length of middle foot

B. Sloped Fracture (slope greater 1" in 5")
1. < 1/4 length of middle foot
2. between 1/4 and 1/2 length of foot
3. between 1/2 and 3/4 length of foot
4. > 3/4 length of middle foot

C. Other

CLASS II. Above Notch (AN) Static Bending

A. Straight Fracture (slope 1" in 5" of less)
1. < 1/4 depth of remaining above notch area
2. between 1/4 and 1/2 depth of remaining above notch area
3. between 1/2 and 3/4 depth of remaining above notch area
4. > 3/4 depth of remaining above notch area

B. Sloped Fracture (slope greater 1" in 5")
1. < 1/4 depth of remaining above notch area
2. between 1/4 and 1/2 depth of remaining above notch area
3. between 1/2 and 3/4 depth of remaining above notch area
4. > 3/4 depth of remaining above notch area

C. Other

CLASS III. End Foot Dynamic Impact Testing

A. One-piece Fracture

B. Two-Piece Fracture

C. Other

Example: A Class IA1 fracture is located between the notches, is straight, and is less than ¼ the length of the middle foot.

APPENDIX C

Sample sizes for the pallet component treatment groups were calculated with the following equation from ASTM D-2915-84, Section 3:

$$n = (\frac{t}{0.05} \times CV)^2$$

where n = sample size

s = standard deviation of specimen values

X = Specimen mean value

COV = coefficient of variation, s/X

0.05 = precision of estimate for stringers and notched segments

0.10 = precision of estimate for end feet

t = value of the *t* statistic from Confidence Interval Table

The sample size depends on the factor being measured. For stringers and notched segments, the factor was strength. For end feet, the factor was the number of impacts to failure, or impact resistance. The equation determines the sample size required to obtain valid conclusions about the factor.

To determine the COV for a population of pallet components, 40 new, unbroken samples of that component were tested to failure. These forty samples gave an estimate of the mean, standard deviation, and COV for the population.

A confidence interval (CI) of 75% was used for estimating the *t* value. The *t* value for 40 samples and a 75% CI is 1.167 (Table 1, ASTM D-2915).

Sample sizes needed for valid comparisons between treatment groups are given in the tables below. The required size was rounded up to give a even number and to reduce possibility of needing additional samples.

Table C.1: Sample Size for Stringers

Group	Average (lbs)	Standard Deviation (lbs)	COV (%)	Computed Sample Size	Actual Sample Size
Initial or Unreinforced Strength					
1-1/2" oak	1305	188	14.4	12	30
2-1/2" oak	1951	404	20.7	24	30
1-1/2" SYP	781	194	24.8	33	40
2-1/2" SYP	1285	268	20.9	24	40
1-1/2" YP	1295	286	22.1	15	30
Repaired Strength					
1-1/2" oak	1528	250	16.4	15	30
2-1/2" oak	2579	591	22.9	29	30
1-1/2" SYP	916	245	26.7	39	40
2-1/2" SYP	1402	355	25.3	35	40
Reinforced Strength					
1-1/2" oak	2286	210	9.2	5	30
2-1/2" oak	2416	383	15.6	14	30
1-1/2" SYP	1540	413	26.8	40	40
2-1/2" SYP	2671	667	25.0	35	40
1-1/2" YP	1745	250	14.3	12	30

Table C.2: Sample Size for Notched Segments					
Initial Strength					
Group	Average (lbs)	Standard Deviation (lbs)	COV (%)	Computed Sample Size	Actual Sample Size
1-1/2" oak	5550	805	14.5	12	30
2-1/2" oak	8864	1375	15.5	14	30
1-1/2" SYP	3042	860	27.0	40	40
2-1/2" SYP	4799	863	18.0	18	40
Repaired Segments					
1-1/2" oak	3714	865	23.3	30	30
2-1/2" oak	7823	1650	21.1	25	30
1-1/2" SYP	2007	590	26.8	40	40
2-1/2" SYP	2300	557	24.2	32	40

Table C.3: Sample Size for End Feet Tests

Group	Average	Standard Deviation	COV (%)	Computed Sample Size	Actual Sample Size
Initial or Unreinforced Impact Resistance					
1-1/2" oak	3.20	1.00	31.3	14	20
2-1/2" oak	1.45	0.51	35.2	17	20
1-1/2" SYP	2.00	0.56	28.0	11	20
2-1/2" SYP	3.05	1.10	36.1	18	20
1-1/2" YP	2.10	0.55	26.2	10	20
Repaired Impact Resistance					
1-1/2" oak	14.8	5.54	37.4	20	20
2-1/2" oak	4.10	1.02	24.9	9	20
1-1/2" SYP	3.60	1.27	35.3	17	20
2-1/2" SYP	4.60	1.53	33.3	16	20
Reinforced Impact Resistance					
1-1/2" oak	6.60	2.45	37.1	19	20
2-1/2" oak	3.15	1.04	33.0	15	20
1-1/2" SYP	2.80	0.96	34.3	17	20
2-1/2" SYP	4.10	1.12	27.3	11	20
1-1/2" YP	4.45	1.19	26.7	10	20

APPENDIX D

Initial Treatment Groups for Repair

To obtain valid statistical comparisons between treatment groups, the groups must be statistically similar for certain physical and mechanical properties. ANOVA and GLM statistical analysis procedures were used to determine if groups were statistically similar. ANOVA was used for groups of equal sample size; GLM on groups of unequal sample sizes.

Table D.1: Stringer Plate Design - 6 groups of 1½" wide oak

Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	1315	3023	9.6	.70	1.43
1½" oak	1315	3002	9.3	.72	1.42
1½" oak	1313	3025	9.4	.70	1.43
1½" oak	1312	3073	9.3	.69	1.43
1½" oak	1311	3097	9.5	.72	1.44
1½" oak	1310	3043	9.3	.72	1.43
ANOVA P-value	.9999	.9266	.7106	.9056	.9493

Table D.2: Stringer Fracture Length - 4 groups of 1½" wide oak					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	1242	3046	9.7	.71	1.42
1½" oak	1330	3113	9.5	.69	1.43
1½" oak	1263	3033	9.4	.72	1.43
1½" oak	1377	2969	9.1	.72	1.44
ANOVA P-value	.2117	.7915	.1342	.7566	.9881

Table D.3: Stringer Fracture Closing - 6 groups of 1½" wide oak					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	1254	3163	9.2	.63	1.41
1½" oak	1250	3103	9.3	.67	1.39
1½" oak	1253	3194	9.4	.65	1.39
1½" oak	1315	3023	9.6	.70	1.43
1½" oak	1312	3073	9.3	.69	1.43
1½" oak	1311	3097	9.5	.72	1.44
ANOVA P-value	.0649	.6917	.4881	.1353	.7743

Table D.4: Stringer Species/Width - 4 groups					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	1315	3023	9.6	.75	1.43
2½" oak	1951	4906	11.9	.70	2.47
1½" SYP	781	2018	12.6	.47	1.47
2½" SYP	1285	2876	12.4	.49	2.46
GLM P-value	.0001	.0001	.0001	.0001	.0001

Table D.5: Notched Segment Plate Design - 5 groups 1½" wide oak					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	5458	30074	10.8	.70	1.41
1½" oak	5550	30721	10.9	.73	1.42
1½" oak	5501	30140	10.8	.69	1.42
1½" oak	5593	30245	11.0	.70	1.40
1½" oak	5613	30658	10.8	.72	1.43
ANOVA P-value	.9191	.9494	.8009	.8934	.7678

Table D.6: Notched Segment Fracture Length - 4 groups 1½" wide oak					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	5993	30350	11.1	.70	1.41
1½" oak	5586	30669	10.8	.73	1.43
1½" oak	5341	30141	11.1	.72	1.41
1½" oak	4953	28275	10.8	.70	1.41
ANOVA P-value	.0170	.5039	.0926	.6221	.8395

Table D.7: Notched Segment Species/Width - 4 groups					
Group	Average Strength (lbs)	Average Stiffness (lbs/in)	Average MC (%)	Average SG	Average Width (in)
1½" oak	5550	30721	10.9	.71	1.42
2½" oak	8959	49133	10.5	.69	2.43
1½" SYP	3042	16514	11.9	.45	1.47
2½" SYP	4799	26224	12.3	.54	2.45
GLM P-value	.0001	.0001	.0788	.0001	.0001

Table D.8: Reinforced Stringer Species and Width			
Group	Average MC (%)	Average SG	Average Width (in)
1-1/2" unreinforced oak	9.6	.75	1.43
1-1/2" reinforced oak	11.5	.72	1.48
ANOVA P-value	.0001	.6555	.7838
2-1/2" unreinforced oak	11.9	.70	2.47
2-1/2" unreinforced oak	12.5	.67	2.43
ANOVA P-value	.0998	.2118	.6698
1-1/2" unreinforced SYP	12.6	.47	1.47
1-1/2" reinforced SYP	11.9	.47	1.51
ANOVA P-value	.0725	.8388	.1587
2-1/2" unreinforced SYP	12.4	.49	2.46
2-1/2" reinforced SYP	12.4	.45	2.53
ANOVA P-value	.3233	.0983	.0807
1-1/2" unreinforced YP	11.8	.45	1.53
1-1/2" reinforced YP	12.5	.47	1.50
ANOVA P-value	.1569	.5443	.4398

Table D.9: End Feet Plate Design - 2 groups of 1½" wide oak				
Group	Average Impacts to Failure	Average MC (%)	Average SG	Average Width (in)
1½" oak	3.20	8.6	.73	1.42
1½" oak	3.25	8.6	.72	1.41
ANOVA P-value	.8735	.3265	.4587	.7693

Table D.10: End Feet Fracture Type - 2 groups 1½" wide oak				
Group	Average Impacts to Failure	Average MC (%)	Average SG	Average Width (in)
1½" oak	2.80	9.0	.72	1.40
1½" oak	2.70	9.4	.74	1.43
ANOVA P-value	.7578	.0899	.6888	.5498

Table D.11: End Feet Species/Width - 4 groups				
Group	Average Impacts to Failure	Average MC (%)	Average SG	Average Width (in)
1½" oak	3.25	8.6	.72	1.41
2½" oak	1.45[1]	10.9	.72	2.47
1½" SYP	2.00	11.2	.52	1.43
2½" SYP	3.05	11.5	.49	2.43
ANOVA P-value	.0001	.0001	.0001	.0001

[1]2½" oak traveled 12" before impact, compared to 6" for other groups. Impacts for 2½" oak were not included in ANOVA test.

Table D.12: Reinforced End Foot Species and Width			
Group	Average MC (%)	Average SG	Average Width (in)
1-1/2" unreinforced oak	8.6	.72	1.41
1-1/2" reinforced oak	8.1	.70	1.44
ANOVA P-value	.0989	.7833	.5687
2-1/2" unreinforced oak	10.9	.72	2.47
2-1/2" reinforced oak	9.8	.69	2.51
ANOVA P-value	.1393	.4888	.5771
1-1/2" unreinforced SYP	11.2	.52	1.43
1-1/2" reinforced SYP	10.6	.57	1.38
ANOVA P-value	.2120	.2339	.0711
2-1/2" unreinforced SYP	11.5	.49	2.43
2-1/2" reinforced SYP	11.8	.53	2.39
ANOVA P-value	.8335	.5543	.1213
1-1/2" unreinforced YP	8.9	.45	1.50
1-1/2" reinforced YP	8.7	.46	1.48
ANOVA P-value	.9117	.7443	.8661

Table D.13: Pallets

Pallet	Average MC (%)	Average SG	Average Stringer Width (in)
OAK 1	11.4	.69	1.53
OAK 2	11.0	.63	1.55
OAK 3	12.0	.66	1.61
OAK 4	10.1	.65	1.50
OAK 5	10.5	.70	1.48
SYP 1	10.4	.45	1.45
SYP 2	10.7	.45	1.35
SYP 3	10.6	.45	1.61
SYP 4	10.1	.48	1.53
SYP 5	10.9	.49	1.50
YP 1	9.5	.41	1.43
YP 2	8.8	.48	1.44
YP 3	8.5	.41	1.40
YP 4	8.8	.42	1.51
YP 5	8.8	.41	1.48

APPENDIX E

ACCELERATED MATERIAL HANDLING PALLET TESTS

Accelerated Material Handling of pallets at VA Tech was modeled after a test setup designed by the Proctor and Gamble Co. [28] to predict the life of pallets in the grocery dry goods industry. It was assumed the average pallet cycle in the dry grocery sector was about 8 weeks, or approximately 6 cycles per year. The accelerated life test included 30 cycles, equivalent to a five year pallet use.

The components of the VPI test cycle consisted of the following:

a. Fork Lift Truck
   CLARK model, abbreviated as FL in this test setup

b. Hand Jack
   hydraulic piston hand pallet jack

c. Unit Load
   1400 pounds of pelletized fertilizer, packed in 50 lb. bags. Bags were stacked on slipsheet to 48x40 shape of pallet. Perimeter of load supported by plywood sides. The slipsheet gave uniformly distributed load to pallets and aided transfer of load to and from pallet.

d. Palletizer/Depalletizer
   A flat deck anchored to floor holds unit load between cycles. Test pallets were placed next to deck. Flat push block attached to FL tines was used to push unit load onto pallets to begin cycle and off pallets at the end of cycle.

e. Staging Area
   Cement floor of test site. Used for sluing with FL, to move pallet so FL could enter from notch side, or to transfer pallet to hand jack.

f. Trailer
   Simulated trailer with plywood sides built on wall at test site. Pallets in storage on one side of the "trailer" allowed only a 50" space for loading and unloading test pallets.

g. Transport Simulator
   A vibration test designed to simulate transportation of palletized goods by truck or rail. This component was not included for pallets in this research, as it was added to the VA Tech test midway through pallet testing.

h. Static Rack

Supported pallets in RAS mode with 44" span. Rack height was 6 feet from floor. Pallet was placed on rack, the FL backed out, then pulled back in and removed pallet. No long term racking was used.

i. Stack

A pallet at ground level loaded with loose, stacked fertilizer bags. Pallet was placed in stacked storage, the FL backed out, then pulled back into pallet and the pallet was removed.

j. Flow Rack

Supported pallets on rollers in RAD mode with 26" span. Pallets rolled on conveyor, inclined at 5°, for 2 feet. Pallet travel was halted when the bottom leading edge deckboard met metal stops placed 26" apart. Pallet was unloaded from flow rack, opposite the end where loaded.

The test sequence (one cycle) of these components is below. A schematic diagram is given on the next page.

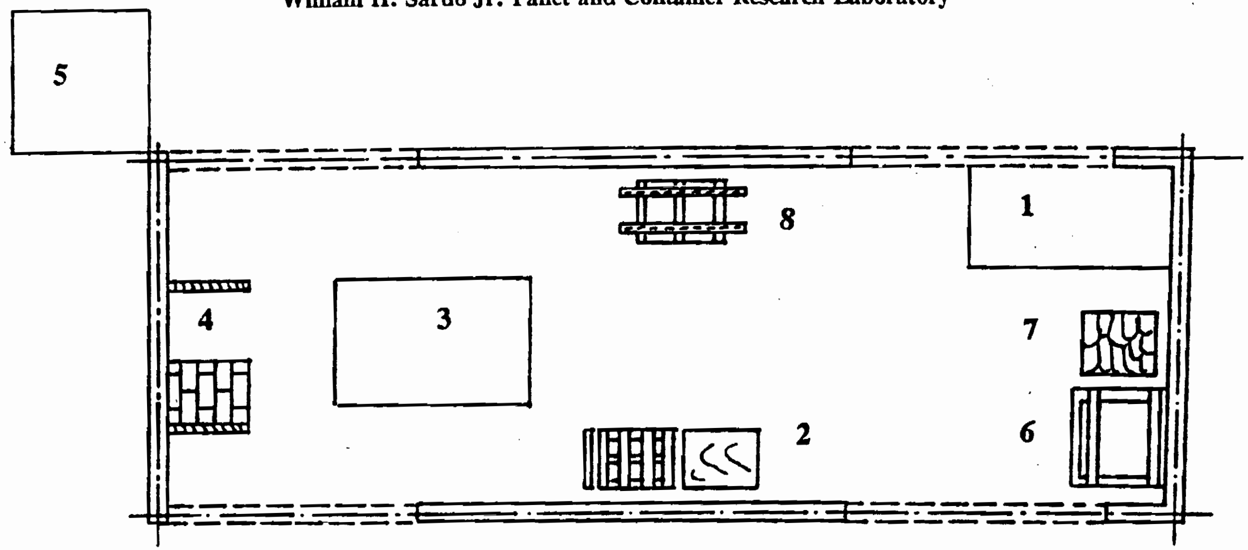
1. Transfer unit load to pallet
2. Move pallet to staging area and slew with FL
3. Pick up pallet from notched side and load in trailer.
4. Pick up pallet from notched side and unload from trailer.
5. Load pallet in trailer with hand jack.
6. Unload pallet from trailer with hand jack, move pallet to staging area.
7. Pick up pallet with FL, place pallet on static rack storage.
8. Remove pallet from static rack storage.
9. Move pallet to stack storage.
10. Remove from stack storage.
11. Move pallet to flow rack.
12. Remove from opposite end of flow rack.
13. Return to beginning and transfer unit load from pallet.
14. Inspect for damage.

Pallet was handled 9 times per cycle:

5 - FL entry in 40" side
2 - FL entry in 48" notched side
2 - hand truck entry in 40" side

VPI UNIT LOAD MATERIAL HANDLING "FAST TRACK"

William H. Sardo Jr. Pallet and Container Research Laboratory



Material Handling Sequence:

Number of Handlings	Station	Description
	1	Empty Pallet Storage
1	2	Palletizer
2	3	Staging Area
3	4	Trailer
4	3	Staging Area
5	4	Trailer
6	5	Transport Simulator
7	6	Static Rack
8	7	Stack
9	8	Flow Rack
10	2	Depalletizer

VITA

John W. Clarke was born in Norfolk, VA on August 25, 1966. He moved to Orange County, and later Madison County, where he graduated from high school in 1984.

He entered VA Tech in 1984 and received a B.S. in Forest Products Utilization in 1988. He worked for Koppers Industries, Inc., a railroad crosstie treating plant in Salem, VA, as a yard foreman for two years. He returned to VA Tech in 1990 and received a M.S. in Wood Science and Forest Products in July, 1992.

He is married to the former Tiffany Sutherland, and they have a son, Will, born on April 11, 1992.