THE EFFECT OF STRINGER DESIGN AND LEADING-EDGE DESIGN
ON THE STRENGTH CHARACTERISTICS
OF WOODEN PALLETS

by

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PART I

The Purpose of Pallet Research

Introduction

A pallet may be defined as a shallow, portable platform designed to permit the mechanical handling and tiering of unit loads of goods and materials by fork trucks, hand pallet trucks, cargo slings, etc. Pallets are manufactured from numerous materials including steel, aluminum, plastics, and a variety of forest-product materials, such as lumber, plywood, and fiberboard. Forest-product industries enjoy an almost total monopoly in the manufacture and supply of general-purpose pallets in North America. As a result, pallet and container manufacturing requires nearly 20 percent of the total annual hardwood lumber production in North America.

Wooden pallets may be classified into three broad categories, that is, expendable, special purpose, and general purpose (7, 8).

1. Expendable pallets, which are referred to as shipping pallets, have a short usable life expectancy and are often discarded after a single use. They are of minimal construction and are often of block and picture-frame designs. Because of their short life expectancy, their cost-use ratio can be higher than that of any other type of pallet. Economy of construction should be a prime design criterion. Only the physical size and weight of the unit load need to be considered when designing these minimal cost assemblies.

2. Special-purpose pallets are designed to support a particular single product. They may be patented pallets containing a construction feature assuring a specific performance. Special-purpose pallets may be designed to support safely dangerous commodities, such as corrosives and explosives; commodities containing a high wholesale and retail value per unit load, such as alcoholic beverages; or irreplaceable goods and commodities, such as specialized electronic devices for transportation to remote scientific outposts. The cost of special-purpose pallets is often negligible compared to the cost of damaged or destroyed unit loads on these pallets. Therefore, these pallets may have a large factor of safety incorporated. Generalized design criteria may, for this reason, not apply to these assemblies.

3. General-purpose pallets are referred to as reusable or permanent warehouse pallets. These pallets must often be designed according to rigid specifications (4, 8) to support

a variety of products and unit loads during repeated long-term uses. Such pallets should be versatile and satisfy the requirements of any handling system. Therefore, they are ideally suited for use in pallet exchange programs and pallet pools.

The purpose of this research project was to optimize the design of wooden pallets using four effective laboratory testing techniques. The scope of this research was restricted to the design of general-purpose wooden pallets, although certain of the conclusions may, at times, be applicable to expendable and special-purpose pallets.

Background

A sound and meaningful laboratory testing program is imperative for the effective and efficient evaluation and determination of pallet-performance characteristics (3, 9). Reliable pallet field trials may require several months, or even years, of continuous planning, execution, and inspection before any valuable information is derived. A laboratory testing program can provide equivalent essential information on strength and durability, such as critical design criteria, after only a few hours of observation and evaluation. But the program must closely simulate the conditions found within an actual handling and transportation environment as well as reproduce actual damage.

The wooden pallet is fallaciously considered by many to be a relatively homogenous product. Basic design principles are seldom applied to its design. Too often this product is manufactured by inadequately fastening a minimal number of parallel deckboards to two or more stringers or block and stringerboard combinations.

Whenever performance criteria are required, it is invariably only the load-carrying capacity, the deckboard and stringer separation resistance, and/or the diagonal rigidity that are considered. Although these properties, and the findings based on traditional tests used to determine them, have long been recognized as invaluable in pallet design (1, 2, 6, 14), they are inadequate for many types of wooden pallets.

Methods of determining these properties are documented in many standards and publications (1, 2, 6, 14). These long-accepted traditional tests include the static load-capacity test, the deckboard and stringer separation test, the 14-foot revolving-drum and the corner-drop tests used to determine diagonal rigidity.

Harvey (5) reports that "a pallet should withstand all the working stresses for which it has been designed, plus a certain degree of mishandling. This degree of mishandling will govern the pallet design far more than the idealized function of a pallet, ie., the supporting of a load". The load-carrying capacity of a pallet has been traditionally determined by performing the static load-capacity test (2), but a reusable wooden pallet rarely suffers a static failure.

Permanent wooden pallets can support static loads far in excess of those actually applied. For example, the Grocery Manufacturers of America's standard pallet can, under static conditions, support loads in excess of 100 tons. In terms of stacking, this represents over 80 loaded grocery pallets stacked one upon the other. Obviously, the static load capacity of reusable wooden pallets cannot be considered a principal design criterion.

Deckboard and stringer separation tests have been used to determine the static separation resistance of pallet joints (15). Deckboard sections are nailed to stringers, simulating a pallet joint. A static force is applied to the section in the direction along the shank of the fastener and the sections are pulled apart. Failure is by one of three modes: (a) the fastener shank pulls out of the stringer section, (b) the fastener head pulls through the deckboard section, and (c) a combination of shank pull-out and head pull-through. These tests result in valuable basic information for pallet design, but pallet failures are not typically of this nature. Failure is usually by a combination of impact or dynamic shear and withdrawal.

One purpose of the revolving-drum test and the principal purpose of the corner-drop test are to determine the diagonal rigidity of the pallet. This is accomplished by measuring the change in length of the pallet diagonals. During this test, a pallet may fail as a result of excessive diagonal deformations. Secondary failures may develop in many high-density lumber, stringer-type, reusable wooden pallets, when subjected to tests aimed at finding diagonal rigidity. These secondary failures may be predictable in nature and can be typically caused by stringer-end splitting (Figure I-1). These splits may run across the end of the stringer through the stringer-nail locations. As a result, the stringer-leadboard joint is weakened and the leadboard separates from the damaged stringer.

Stern and Dunmire (27) have observed that yellow-poplar pallets, being lighter in weight than similar pallets made from oak or hickory, perform better in the laboratory when tested in this traditional manner. Yet, they conclude that the field performance of oak or hickory pallets is much superior than the field performance of similar yellow-poplar pallets.

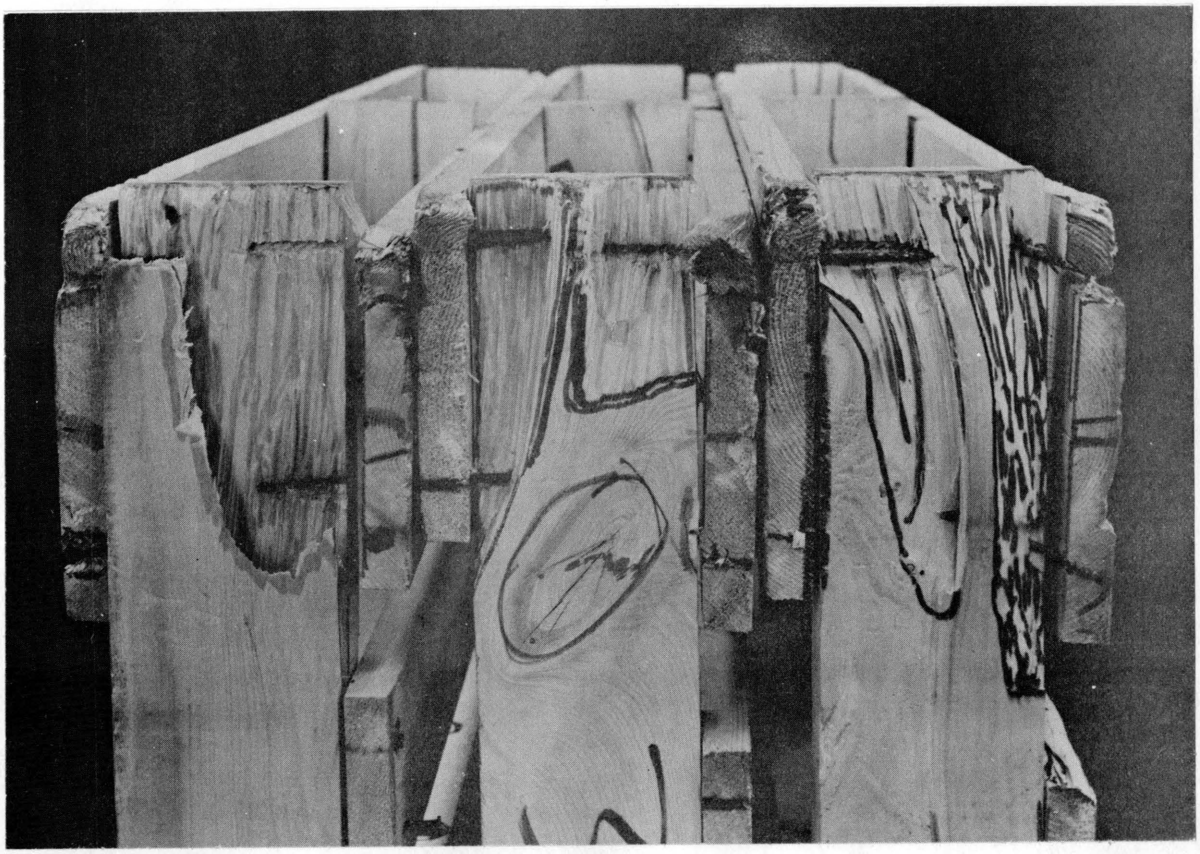

Figure I-1. Typical secondary damage to hardwood stringer-type pallets tested to determine their diagonal rigidity. (Photo, courtesy of Environment Canada. Eastern Forest Products Laboratory.)

It has recently been shown, during field studies conducted by the Canadian Forestry Service (9), that over 70 percent of all field damage to reusable wooden pallets occurs along the leading edge. But this damage is not caused by splitting within the stringers. The repeated impacts of fork-lift trucks against the upper leading edge of a pallet pushes the leadboard back from its initial flush position (Figure 1-2). This action bends the nails fastening the leadboard to the stringers and weakens the joint. Finally, the leadboard is pried from the pallet as the heels of the forks strike again and again against the upper leading edge (Figure 1-3). The orientation of the bent nails, which fastened the missing leadboard, indicates this pushing and prying action by the forks (Figure 1-4).

These observations have led to the belief that a totally new concept of pallet research is required to represent accurately field conditions, to reproduce faithfully pallet damage in the laboratory, and to develop design criteria for the development of improved wooden pallets (9). The wooden pallet cannot be considered to be a single homogenous unit. Instead it contains a number of distinct areas within the unit. The effects of handling and shipping hazards on these areas must be given prime consideration in the design of pallets.

Research Scope

The wooden pallet contains four principal design areas, each containing one or more components. These areas are (1a) the stringers and (1b) the block and stringerboard combination, (2) the upper and, in double-faced pallets, the lower leadboards which contain one or more spaced or butted members, (3) the top and the bottom center deck areas, and (4) the mechanical fasteners used to assemble the components.

The stringers or the block and stringerboard combination are most important in reusable wooden pallets of good quality. Stringers provide openings for the entry of mechanical handling devices. They also provide much of the stiffness required in reusable pallets. Damaged or missing deckboards, including leadboards, can be easily replaced. Effective stringer repair can be difficult, although cleating them or inserting an additional adjoining stringer is usually feasible and economical.

Many stringers contain two notches or cutouts along their bottom. These stringers may be damaged more readily than full stringers when struck during haphazard fork lift entry or when the stringers strike barriers or obstacles during handling. Stringers may

Figure 1-2. The leadboard has been pushed back from its initial flush position in this hardwood stringer-type pallet tested in the field. (Photo, courtesy of Environment Canada. Eastern Forest Products Laboratory.)

Figure I-3. Typical failure of hardwood stringer-type pallet tested in the field. (Photo, courtesy of Environment Canada. Eastern Forest Products Laboratory.)

Figure I-4. Bent nails of damaged hardwood stringer-type pallet tested in the field suggest a pushing and prying type of failure. (Photo courtesy of Environment Canada. Eastern Forest Products Laboratory.)

also fail in the region between the two notches. Such failures can occur during stringer seasoning or when the stringers are exposed to abnormally high flexural stresses.

Part II of this thesis covers the design of notched pallet stringers. The notch end fillet configuration is studied in an attempt to minimize impact, flexural, and seasoning failures.

The upper leading edgeboards, where more than 70 percent of all pallet damage was observed (9), are of most critical design importance. The pushing and prying action that occurs when pallets are exposed to typical handling and shipping environments, must be resisted. These members also add to the bearing surface of the top deck. Damage to, or the loss of, an upper leadboard can substantially decrease the bearing surface and weaken the assembly. In addition, the upper and lower leading edges of wooden pallets provide a major part of their diagonal rigidity. Furthermore, the loss of upper leadboards can result in an unstable unit load prone to be damaged by mechanical handling devices.

Both the immediate and delayed axial withdrawal resistance of helically threaded pallet nails is greater in high-density red oak than in either low-density eastern hemlock or Douglas fir (10). These conclusions suggest that there may be a correlation between the specific gravity of the stringers and leadboards of the wooden pallet, on the one hand, and the resistance of these members to fork lift and other hazards, on the other hand.

Part III of this thesis covers the effect of specific gravity of stringers and leadboards on the impact resistance of wooden pallets. A mathematical expression is developed that describes the expected impact resistance of any stringer and leadboard combination.

The principal purpose of the center-deck area is to provide a sufficiently strong bearing surface for the unit load during handling, stacking and tiering. The center-deck area is usually protected from shock hazards by the outside leadboards and outside stringers; although proper design of the members in the center-deck area can enhance the strength of these outside members. Damage to the center deck area is usually observed only if excessively weak members are incorporated in this area. Center deckboards containing excessive cross-grain or large knots often fail when exposed to shock loading as incurred when the tines of a fork lift enter a pallet in a plane not parallel to the deck. In such an instance, the toes of a tine can strike a deckboard and, when the jointing of this member and/or the member itself are weakened, the deckboard can be torn from the assembly.

Damage to this region of the wooden pallet accounts for approximately 10 percent of all pallet damage which can usually be repaired readily and economically (9). Therefore, many of the weak North American woods may be successfully utilized in this area of the wooden pallet. This aspect of the wooden pallet is not studied in this thesis.

In most instances wooden pallets consist of two commodities, that is, the wooden members and their mechanical fasteners. Recent studies (9) indicate that wooden pallets are only as good as the mechanical fasteners used for their assembly. Thus, the mechanical fasteners may be the "weakest link" in a pallet. Fasteners, inadequate in their ability to transmit impact shear loads without excessive deformation, can cause the loss of the upper leadboards. Similarly, mechanical fasteners can add to or detract significantly from the diagonal rigidity of wooden pallets (16). The effect of the fastener design has been studied by Stern (10-26) and is not covered in this thesis.

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PART II

The Effect of Stringer-Notch Geometry on Pallet Strength and Stiffness

Introduction

Stringers, or block and stringerboard combinations, are critical parts of both reusable and expendable wooden pallets. Stringers contribute to pallet strength, stiffness, and durability. Stringers and stringer notches provide openings for the entry of mechanical handling devices. Fractured stringers accounted for 14 percent of all damage to two-way entry, stringer-type, reusable wooden pallets during recent field tests conducted by the Canadian Forestry Service (5). These fractures were the second largest single cause of pallet failures. The largest single cause of pallet failure was leadboard-stringer separation (5).

Many stringers contain two notches or cutouts along their undersurface. These notches facilitate four-way entry of the forks of lift trucks. They also weaken the stringers significantly. Kurtenacker (3) reported that hickory stringers containing no notches sustained before failing, on the average, 27 repeated impacts by a 90-pound hammer falling through a drop height of 62 inches. Similar stringers with conventional notches failed after only one drop from 28 inches. The notch configuration influenced the strength of the stringers. Squared and trapezoid notches in yellow-poplar stringers made the stringers considerably weaker than the more conventional rounded notches.

The notches act as stress raisers which decrease the overall strength of notched stringers. Their ends may fail when struck during fork entry, when pallets are slued, and when pallets strike obstacles during handling. These failures along the grain are caused by shear stresses parallel to the grain.

Notched stringers also fail in the center region between the notches. These failures may be caused (a) by excessive bending stresses which can develop during pallet handling and end-racking of loaded pallets and/or (b) by stresses which may develop during seasoning. The latter may happen if an appreciable moisture gradient develops around the notch fillet as a result of moisture loss through the end grain.

The fillet curvature and notch manufacturing techniques may affect the extent of the stress concentration and, hence, the ultimate flexural strength of the stringers.

Stieda (8) studied stress concentrations in (a) 0.375 x 0.08-inch, (b) 0.375 x 2.0-inch, (c) 0.5 x 0.08-inch, and (d) 0.5 x 2.0-inch notches cut into the tension face of 1 x 1 x 16-inch western hemlock, western balsam fir, and eastern white cedar beams tested in flexure. It was confirmed that failure at the notches was caused by a combination of shear and tension perpendicular to the grain. Stieda (8) also compared 0.375 x 0.08-inch round and square notches cut into the tension face of identical 1 x 1 x 16-inch beams tested in flexure. He observed no significant difference in the flexural strength of these beams. It appears, however, that quite a different response may be observed in larger, full-size, notched pallet stringers cut with fillet radii of various sizes.

Stringer notches are commonly manufactured either with a band-saw or a stringer-notcher. Band-sawn notches may contain irregularities which increase stress concentrations; whereas notches cut with a notcher are smooth and uniform.

The purpose of this study was to optimize the curved end fillet configuration of the conventional notch. The handling resistance and the flexural strength of pallet stringers with fillet radii of various sizes were studied by performing both shear and flexural tests. Notches cut with a band-saw and a stringer-notcher were studied. Additionally, attempts were made to reduce the incidence of stringer fracture during pallet handling and moisture desorption. Stringers were reinforced adjacent to the inner notch fillets, and longitudinal moisture movement through the end grain of the notch end fillets was retarded.

Test Materials

Red oak (Quercus rubra L.), a common species for pallet manufacturing throughout Appalachia (4) and other regions of eastern North America (2), was selected for the study. The required 2 x 4 x 48-inch stringers were obtained from the Petawawa Forest Experiment Station, located at Chalk River, Ontario, Canada. Thirty-six trees yielding thirty-eight 12, 14, and 16-ft. sound logs were selected from a well-drained red oak and white pine ridge, typical of the area (1). Only merchantable-size trees (14-inch d.b.h. or greater) were selected, yielding 1,364 fbm (log scale).

The freshly cut logs were flat-sawn into full-length 2x4-inch boards. Straight-grained, defect-free, 4-ft. lengths were selected from the available material.

Of the available 2 x 4 x 48-inch stringers, 192 were randomly selected to determine the effects of the end fillet radii. The $1\frac{1}{2}$ x 9-inch notches had fillet radii of 0, $\frac{1}{4}$, $\frac{1}{2}$, 1, $1\frac{1}{4}$, and $1\frac{1}{2}$ inches (Figure II-1). Ninety-six stringers had band-sawn notches and an equal number had notches cut on a stringer-notching machine cutting perpendicular to the long axis of the stringer (Figure II-2). These notched stringers were subjected to both impact shear tests and flexural tests, simulating abusive handling and edge racking of pallets, respectively. Three notches were cut into those stringers to be tested in shear and two notches were cut into those stringers to be tested in flexure (Figure II-3).

Six band-sawn and six machine-shaped notched stringers of each fillet configuration were tested in shear. Six shear samples, each simulating the leading quarter of a notched stringer, were obtained from one notched stringer. Thus, a total of 432 samples were tested. Additionally, ten band-sawn and ten machine-shaped notched stringers of each fillet configuration were tested in flexure.

Wooden pallets are usually manufactured from green lumber and are often placed in service before they have had time to season. Consequently, the shear and flexural tests, designed to determine the effects of the various end-notch fillet configurations were performed with freshly sawn green samples. This procedure eliminated the effects of any seasoning defects.

The 2-inch edges were planed prior to notching to assure flat and parallel notches. The stringers were dressed to $1\frac{1}{2}$ x $3\frac{1}{2}$ x 48 inches after notching. To examine the two variables introduced to reduce the incidence of fracture during desorption, 165 stringers were tested in flexure. These stringers were also dressed after machine notching with 1-inch notch fillets, to $1\frac{1}{2}$ x $3\frac{1}{2}$ x 48 inches.

Experimental Methods

1. Shear Test on Fillet Configurations

The stringer impact-shear test was designed to simulate stringer leading-edge impacts resulting from rough handling of pallets when slued or striking an obstacle. In such instances, longitudinal fractures can develop between the stringer leading edge and the outer notch fillet. The stringer impact-shear test reproduces these fractures.

Simulated leading-edge sections were placed on the bed of a Hatt-Turner impact testing machine with the foot end in the upright position (Figure II-4). The samples were positioned in such a manner that the foot of each sample sheared along a line

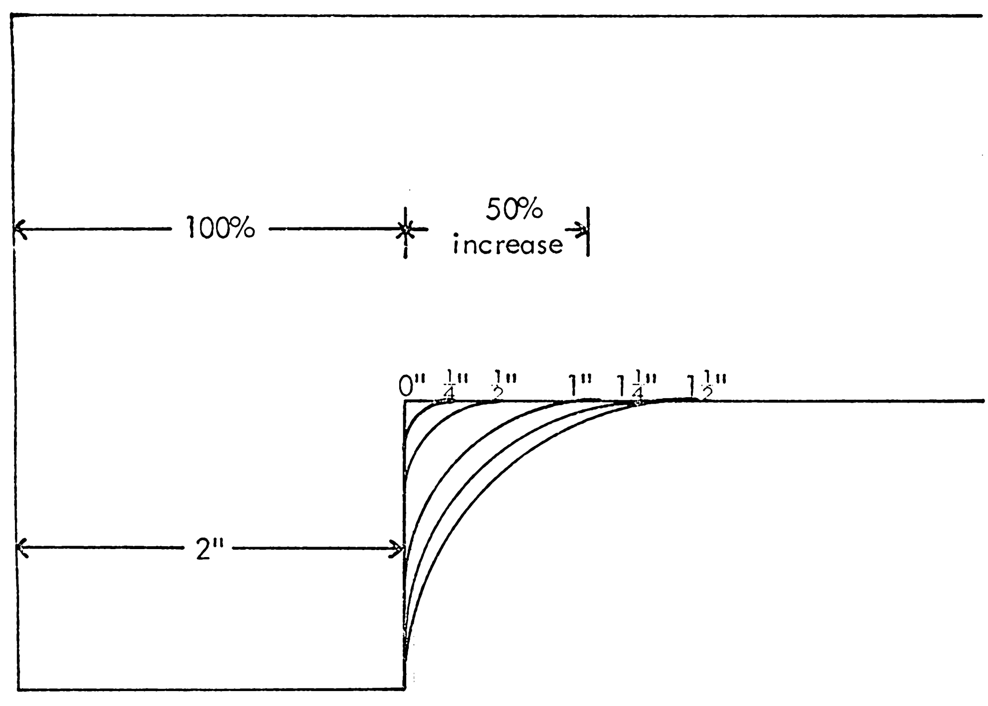


Figure II-1. Notch fillet radii tested in both shear and flexure are shown in actual size.

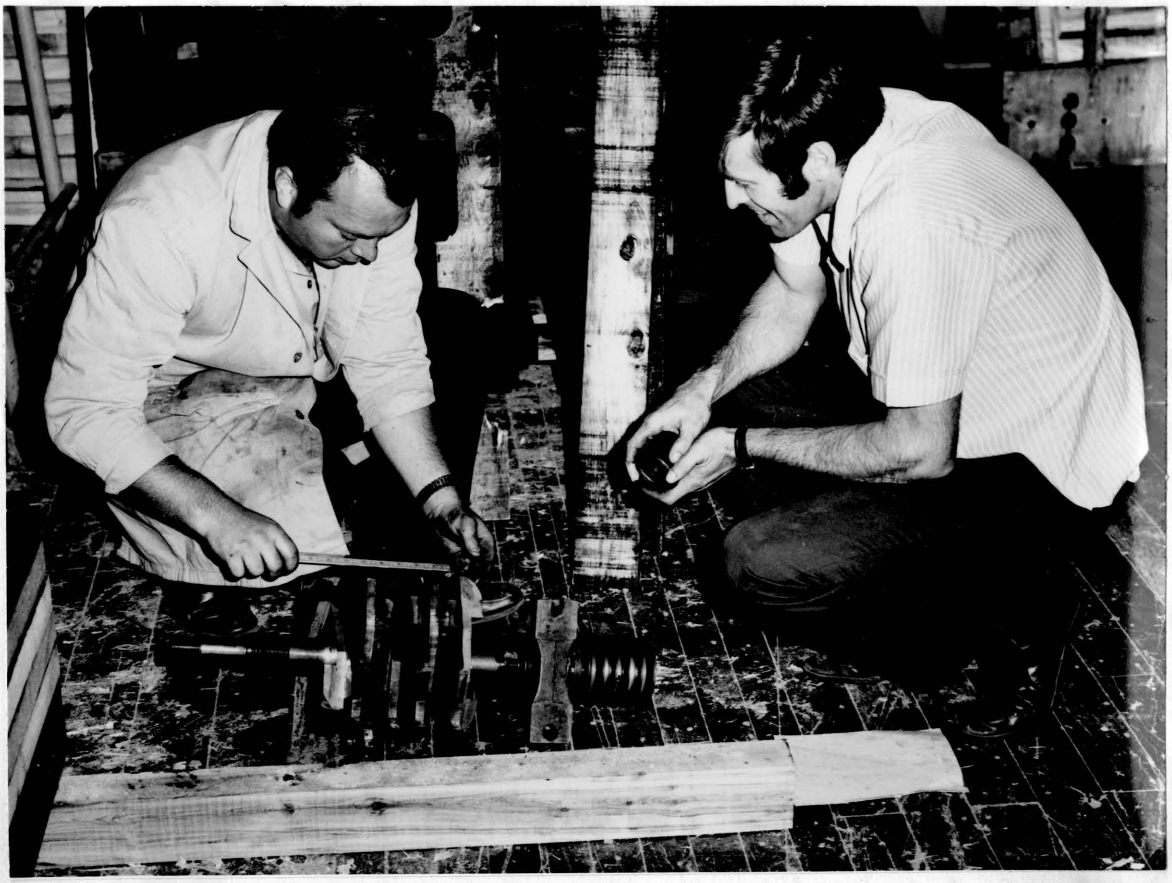
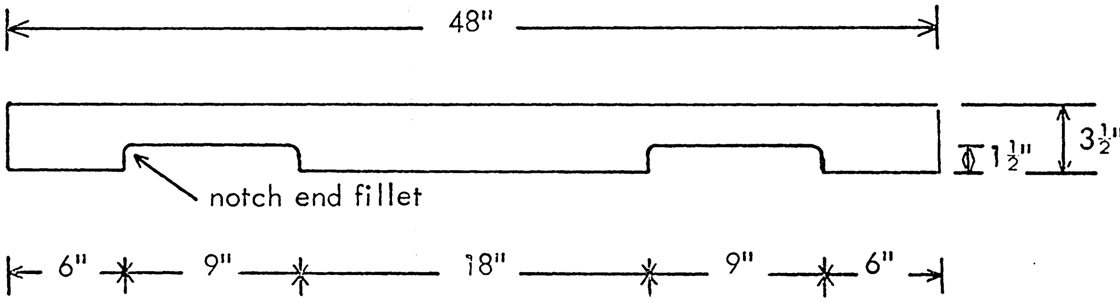
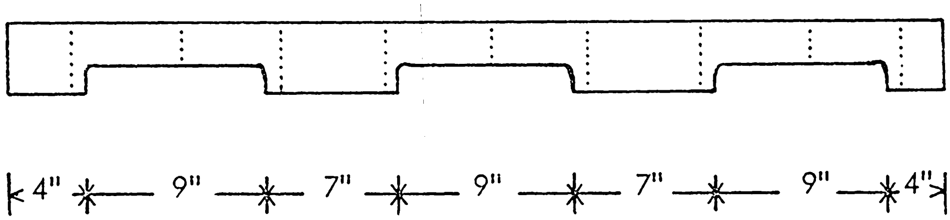


Figure II-2. Cutting head used to manufacture machine-shaped notched stringers. (Photo,courtesy of Environment Canada. Eastern Forest Products Laboratory.)



Notched-stringer configuration for flexural study.



Notched-stronger configuration for shear study.

.... indicates saw cuts used to prepare shear samples.

Figure II-3. Geometry of stringers notched for shear and flexural studies.

Figure II-4. Testing machine and recording devices used to determine the shear resistance of notched pallet stringers. (Photo courtesy of Environment Canada. Eastern Forest Products Laboratory.)

extending to the inner surface of the notch when struck by the drop hammer (Figure II-5). The 103-pound drop hammer was positioned at a height of 14 inches above the sample ensuring total failure of the sample after a single drop.

This method of test does not produce pure shear. A bending couple may develop as the hammer strikes the sample. Failure may, therefore, be caused by shear and tension forces perpendicular to the grain.

Thirty-six band-sawn and an equal number of shaped notch fillets of each fillet radius were tested. The foot length of these samples, commonly 6 inches in full-size stringers, was reduced by 67 percent to 2 inches. The grain direction along the foot-stringer interface can significantly influence the test results. Reducing this area reduces this variable. Furthermore, strength variations among the various fillet configurations become more obvious if only a small foot area is tested.

The impact shear resistance of stringers in two-faced pallets may be increased by the bottom-deckboard nails passing through the weakest shear plane. This case was not investigated.

The impact resistance of each sample was assumed to be proportional to the work required to shear the stringer foot from the sample. The total work at impact causing failure is mathematically equal to the total, potential and kinetic, energy loss of the drop hammer at impact. Thus, the work at impact may be calculated since the weight of the drop hammer, the velocity of the drop hammer at impact, and the acceleration vs. time record of the impact can be measured. The relationship used to calculate the work at impact is developed in Appendix I.

A Schmitt Trigger level detector was used to measure the velocity at each impact. Two horizontal parallel bars, $\frac{1}{8}$ inch in diameter and vertically separated by $\frac{1}{8}$ inch, were affixed to the drop hammer. A collimated light beam, impinging upon a photo resistor, was positioned such that the two bars affixed to the drop hammer cut the light beam $\frac{1}{4}$ inch above the impact surface. The "pulses", thus produced, were shaped and amplified. The interval between the leading edges was measured to the nearest microsecond on a digital counter-timer. The velocity, $\frac{1}{8}$ inch before each impact, was then calculated knowing the time required by the drop hammer to travel a known distance. Although the drop hammer continued to accelerate after its velocity had been measured, calculations show that the expected velocity at impact was less than 1.7 percent greater than the measured velocity.

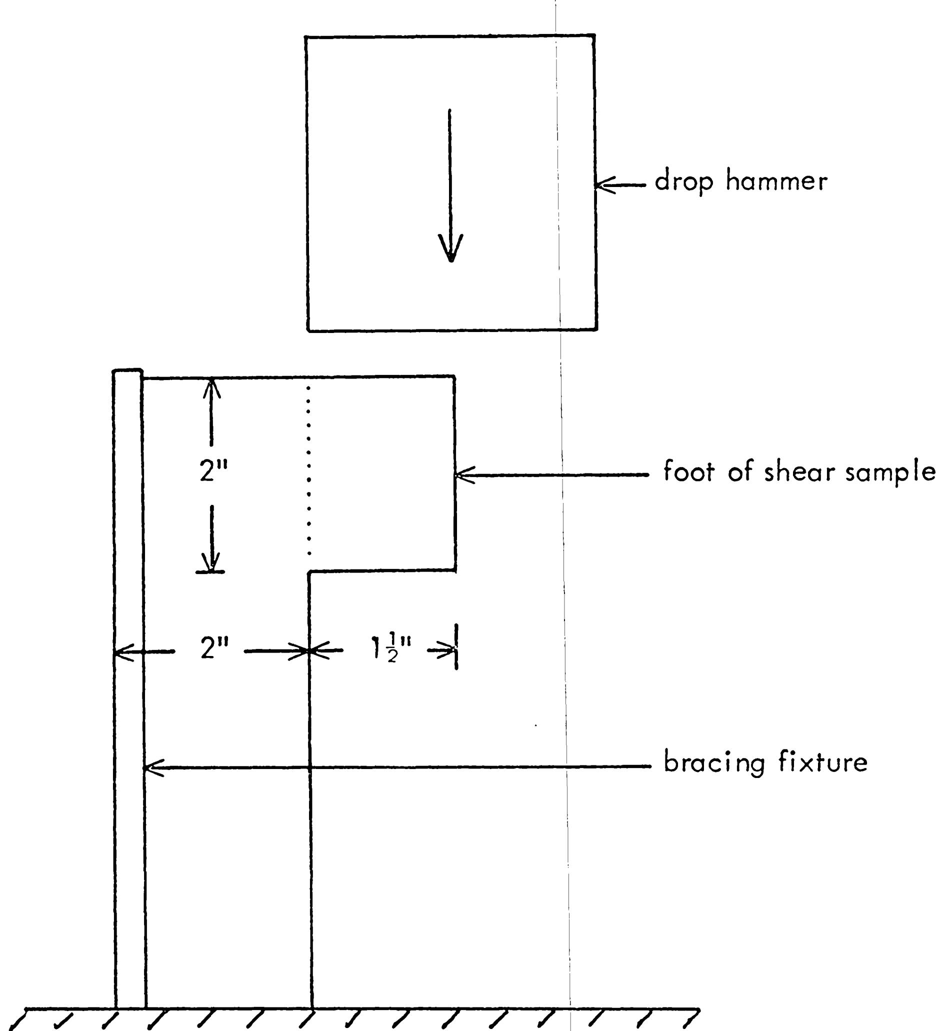


Figure II-5. The free-falling drop hammer shears the foot from the pallet stringer. ... indicates plane of shear.

A piezoelectric accelerometer, affixed to the top of the drop hammer, was used to record the deceleration vs. time pulse of each impact. High frequency resonant vibrations were mechanically filtered from impact pulses. Each impact pulse was amplified and stored on magnetic tape for later display on a storage-type oscilloscope. A photograph was taken of the deceleration vs. time pulse of each impact. An integrating digitizer, interfaced to a programmable desk top calculator, was used to calculate the work required to shear the stringer foot from each sample.

The accelerometer was calibrated by placing it on a small electromagnetic shaker table vibrating sinusoidally at 60 hz. The accelerations associated with this vibration were dis played on a cathode ray tube. A hollow, sealed sphere was securely fixed to the underside of the shaker table. A small, steel ball-bearing was placed within the hollow sphere. The amplitude of vibration was increased until an acceleration of 1 g was attained. At this point, the ball-bearing lifted from the base of the hollow sphere and the smooth sinusoidal vibration became a series of repetitive shocks. This phenomenon was first observed as a kink in the leading edge of the sinusoidal wave form displayed on the cathode ray tube at which point the accelerometer was calibrated to 1 g.

2. Flexural Test on Fillet Configurations

To determine the effect of each fillet configuration in bending, 120 stringers were tested. Ten notched stringers of each fillet radius and each method of manufacture were tested in a flat-bed screw-type compression testing machine. Two support pipes, $2\frac{3}{8}$ inches in outside diameter, were placed 2 inches from the stringer ends on the underside of each stringer. Two similar loading pipes were placed at the quarter points of the span, since quarter-point loading simulates a uniformly distributed load. An increasing load was then applied to the stringer at a constant rate, 0.3 inches of machine-head movement per minute. The maximum deflection at the midspan and the load at failure of each sample were recorded by an XY plotter.

3. Flexural Test on Modified Stringers

Attempts were made to increase the flexural strength of the notched stringers (a) by nail-reinforcing the wood near the inner notch fillet, and (b) by coating the notch surfaces to retard longitudinal moisture movement through the notch ends. A total of 165 machine-notched stringers, having a 1-inch fillet radius, were tested in flexure. One third of these were control stringers, one third were nail-reinforced near the inner notch fillets, and the remaining one third were used to determine the effect of retarding longitudinal moisture movement through the end grain at the notch ends. The notches were manufactured and the stringers were planed green to $1\frac{1}{2} \times 3\frac{1}{2} \times 48$ inches. Five stringers of each lot were tested approximately every ten days for a period of 100 days. The average moisture content near the notch, at each test period, was obtained by the oven-dry method from a random sample taken from each lot.

A cluster of three $2\frac{1}{2} \times 0.138$-inch (crest diameter) helically fluted pallet nails, was driven directly into the underside of those stringers to be nail-reinforced near the inner notch fillets. The cluster was positioned according to the pattern recommended by Stern (6). The two nails of the cluster of three nails were driven 1-inch from the notch end. These nails were driven $\frac{3}{8}$-inch from the sides of the stringer. The third nail was driven 2-inches from the notch end, equidistant from the sides of the stringer. Each nail was countersunk $\frac{1}{8}$ inch.

The longitudinal moisture movement through the notch end fillets was retarded by coating the notch surface with a catalized polyvinyl acetate adhesive. This flexible adhesive penetrated all exposed end grain, thereby reducing the moisture gradient along the center portion of the stringer. A moisture gradient along the center portion of the stringer produces tension perpendicular-to-the-grain stresses due to differential shrinkage across the cross-section.

Test Results

1. Shear Test

High-speed motion-film photographs indicated that the test method used produced relatively pure shear failures. The bracing fixture, securing the test samples to the testing-machine bed, minimized any tendency for the sample to bend. The test samples consistently failed along the straight line extending from the end of the sample to the vicinity of the top of the notch. The failure was abrupt and typically of 1.5-ms duration.

A representative deceleration vs. time pulse of the shear failure is given in Figure II-6. The initial positive-going half-sine pulse is approximately 1.5-ms in duration. The velocity of motion began to increase at the end of this period, indicating a resumption of near free-fall conditions. Therefore, only the initial response need be integrated to calculate the work required to cause shear failure. The smaller secondary pulses shown in Figure II-6, may be caused by frictional forces developed as the drop hammer slides past that portion of the test sample held in place by the bracing fixture. A detailed summary of the work required to cause failure of each machine-shaped and band-sawn notch sample is given in Appendix II.

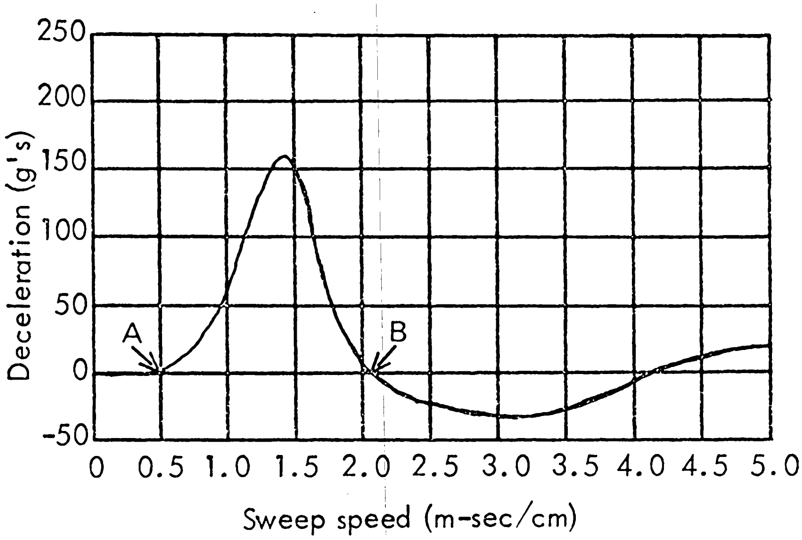


Figure II-6. Typical deceleration vs. time pulse of a band-sawn shear sample cut with a 1-inch fillet radius. The pulse was integrated between points A and B.

The impact test was never used previously. Since 36 replications were performed, the number of required replications can be calculated to produce as accurate test data as are desired.

A linear approximation of the primary response was considered justified across the notch radii examined. A plot of the average work to failure and a linear estimate to best fit for both the machine-shaped and band-sawn notched samples is presented in Figure II-7. Standard statistical methods were used to calculate the linear response by the method of least squares. The correlation coefficients for the machine-shaped and band-sawn samples are 0.746 and 0.764, respectively. Therefore, 55.6 and 58.3 percent, respectively, of the increasing work required to cause failure of the machine-shaped and band-sawn notched samples are accounted for by the increasing notch radius. Although a null hypothesis of linearity is rejected at the 0.1 percent statistical level of significance, the plot of means does not suggest a better fitting second-order curvilinear response for either the machine-shaped or band-sawn notched samples, and the experimental limits prohibit consideration of any higher-order response.

The calculated linear response indicates that the average shear resistance of notched stringer samples cut with $\frac{3}{4}$-inch and $1\frac{1}{2}$-inch machine-shaped or band-sawn notch end fillets is approximately 7.5 and 15 percent, respectively, greater than similar square notches. The plotted response also indicates no significant difference between the shear resistance of machine-shaped and band-sawn notches. However, the band-sawn notches examined during this investigation were carefully cut by expert carpenters and may have contained fewer stress-raising irregularities than hastily produced notches cut under mass-production conditions. It is, therefore, possible that the shear resistance of the tested stringers was somewhat greater than that of commercially produced stringers.

2. Flexural Test

The slope of the load vs. deflection curve for all flexural samples was linear and independent of the notched-stringer geometry, rising to an abrupt failure when splits, extending from the inner notch end fillets, developed parallel to the grain of the stringers. The ultimate loads for each machine-shaped and band-sawn notched pallet stringer are given in Appendix III. Plots of the average flexural strength are presented in Figure II-8. A second-degree polynomial, having one relative maximum, is also plotted.

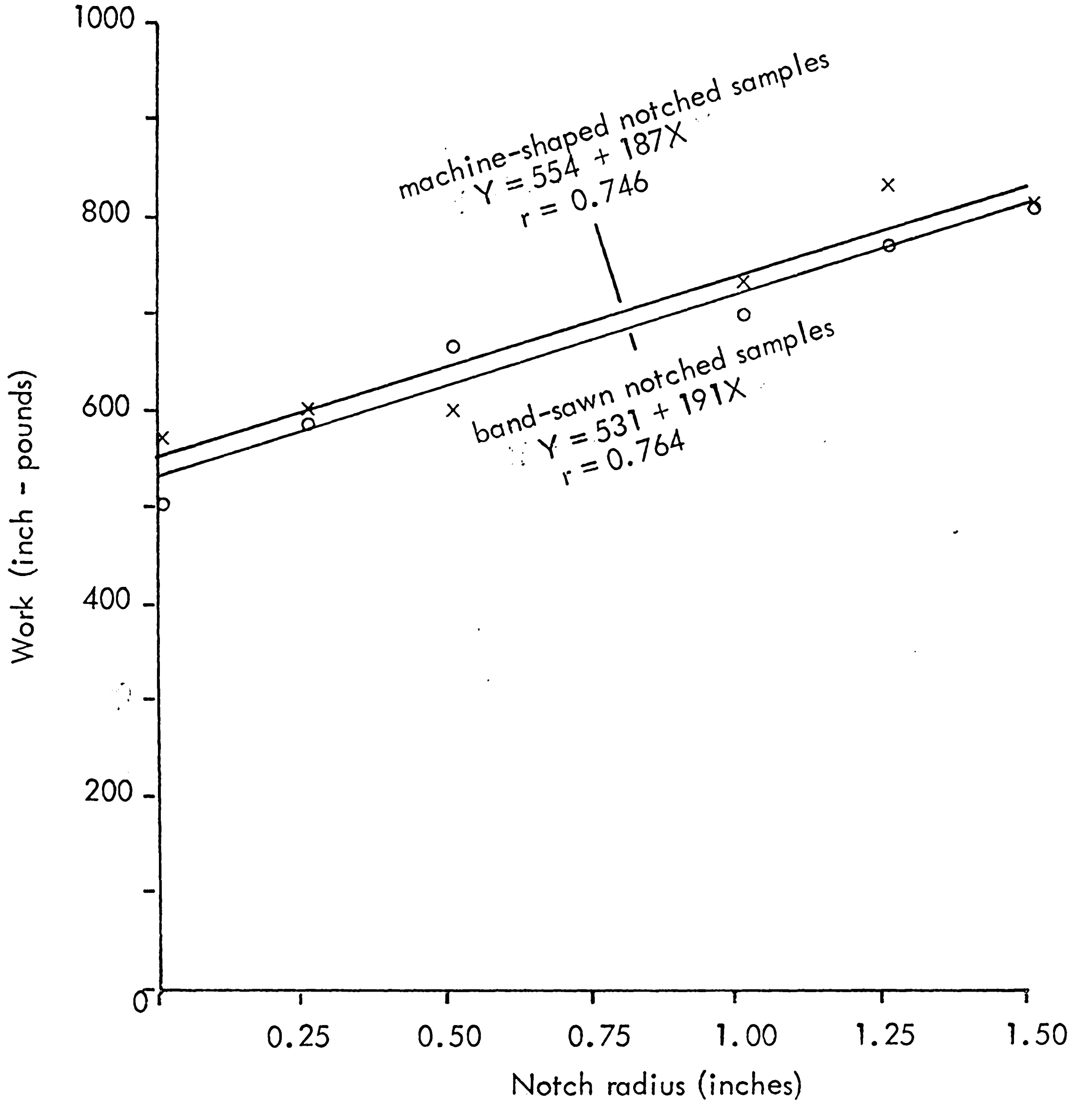


Figure II-7. Work, in inch-pounds, required to shear notched pallet stringers.

x represents plot of means of machine-shaped samples.

o represents plot of means of band-sawn samples.

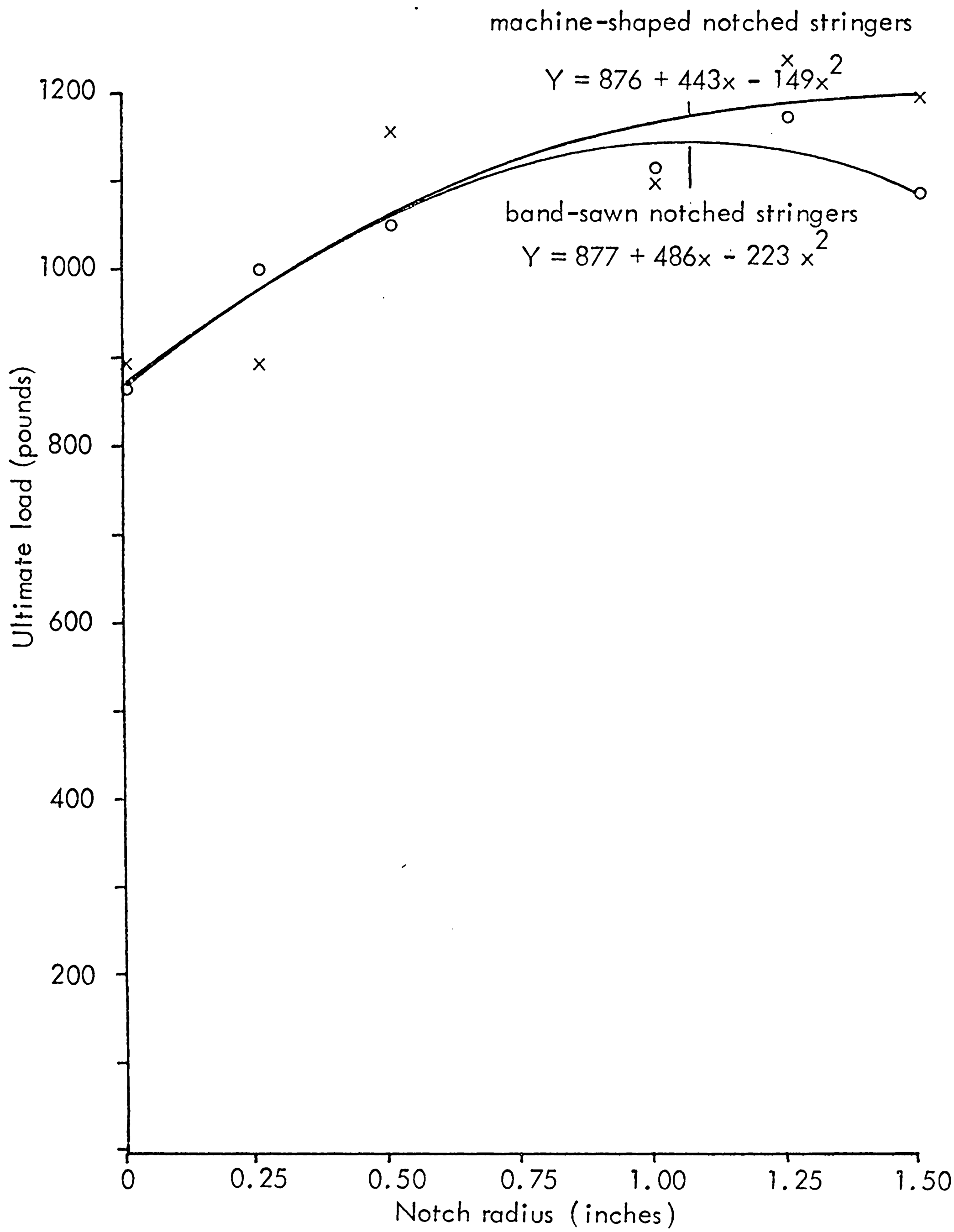


Figure II-8. Ultimate flexural strength of notched pallet stringers.

x represents plot of means of machine-shaped notched stringers.

o represents plot of means of band-sawn notched stringers.

A second-order response was selected since the linear correlation among the machine-shaped and band-sawn stringers is only 0.624 and 0.446, respectively. Additionally, linearity of the machine-shaped stringers is rejected at the 10 percent level of significance and visual examination of the plot of means suggests a second-order response.

The machine-shaped and band-sawn responses rise to a maximum at a notch radius of 1.50 and 1.00 inches, respectively. Again, there is little difference between the response for both notching techniques. This may be due to the fact that carefully manufactured band-sawn notched stringers, containing few stress-raising irregularities, were tested. On the average, the flexural strength of the machine-shaped and band-sawn notched stringers with a notch radius of 1.00 inches was 32 percent higher than similar square-notched stringers.

3. Modified Stringer Tests

Nail-reinforcing caused considerable checking of the stringer base adjacent to the reinforced notch end fillet. These checks rarely exceeded 2 inches along the bottom surface and were limited to the length of the shanks of the reinforcing nails. Of the 330 nail-reinforced stringer notches, 74, or 22 percent, checked in this way.

The liquid adhesive applied to the notch surface effectively coated the notch fillet radii.

Typical load vs. deflection curves for control, nail-reinforced, and notch-coated stringers, tested after a 60-day delay, are shown in Figure II-9. The failures of the control and notch-coated notched stringers tested in flexure were typical. The load vs. deflection curves rose more or less linearly, rising to an abrupt failure at that point where splits, extending from the inner notch end fillets, developed parallel to the grain of the stringers. The nail-reinforced stringers exhibited this characteristic failure only when tested immediately after nailing.

The nail-reinforced stringers had two distinct failure phases during delayed testing. They were similar to those observed by Stern (7). The slope of the load vs. deflection curves were more or less linear until initial failure occurred. At this point, splits, extending from the notch end fillets, developed parallel to the grain of the stringers. After this initial failure had developed, the reinforcing nails delayed total failure of the stringers. The load vs. deflection curves again began to rise slowly until ultimate failure occurred. However, center-span deflection at ultimate failure often exceeded 2 inches.

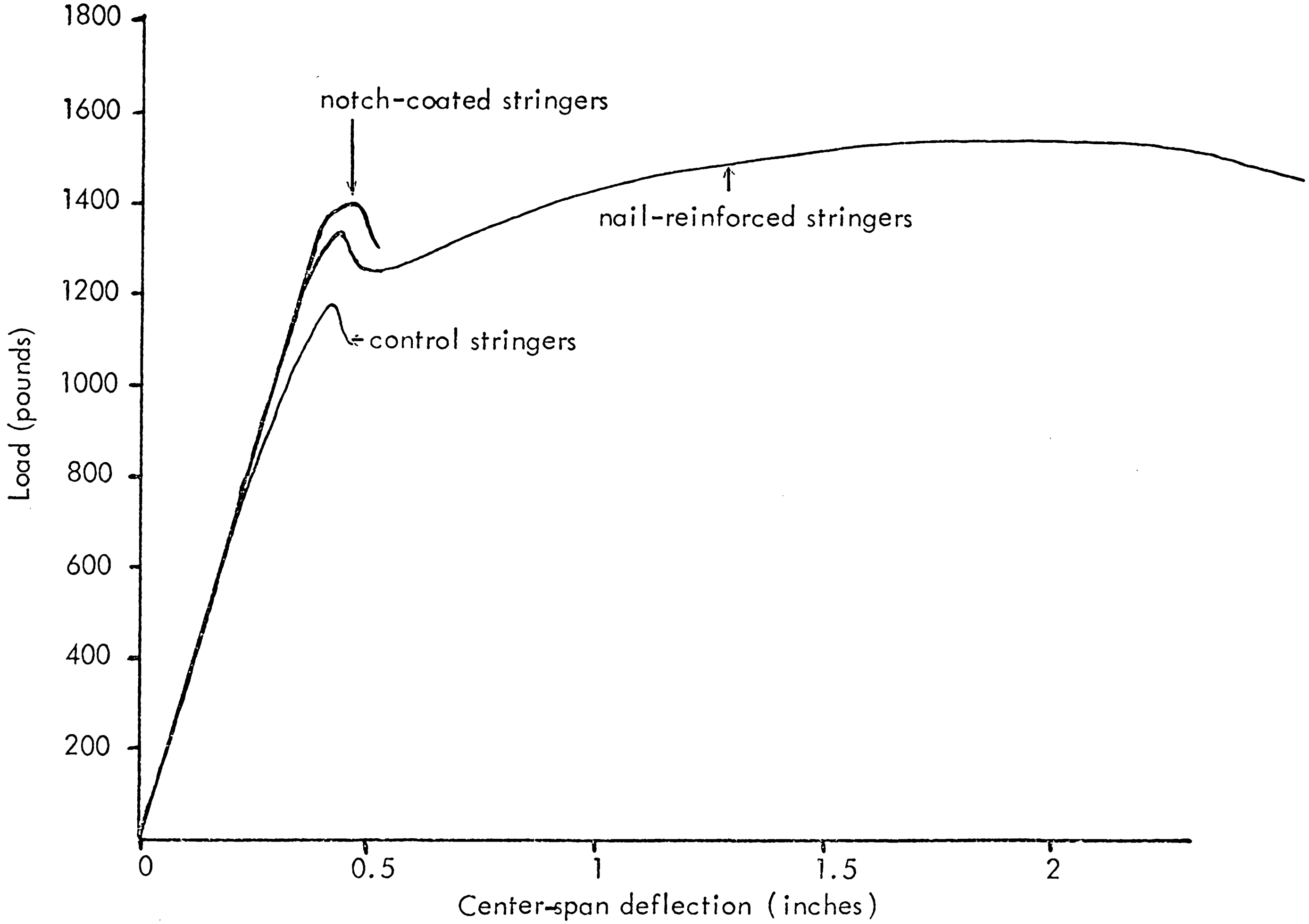


Figure II-9. Typical load vs. center-span deflections of control, notch-coated, and nail-reinforced notched pallet stringers tested in flexure.

As the nail-reinforced stringers seasoned, the wood shrank away from the nail head, thus eliminating its ability to prevent longitudinal splitting. But, when the stringers split at the point of initial failure, the nail heads again came into bearing and the stringers could again carry an increasing test load, although excessively high deflections were observed. The stiffness characteristics of the nail-reinforced pallet stringers decreased appreciably after splitting had occurred and the use of split nail-reinforced stringers cannot be considered desirable. However, nail-reinforced stringers may prevent the total collapse of a pallet should stringer splitting develop during service. Nail-reinforcing may, therefore, add an in-service margin of safety by providing protection against total collapse of a palletized unit load should initial failure occur.

The detailed test data are presented in Appendix III. Table II-1 is a statistical summary of these data. Column 1 of Table II-1 shows the number of tests performed. Column 2 presents the "y" intercepts for a linear response calculated by the method of least squares. Column 3 gives the slope of this linear estimate. Columns 4 and 5, respectively, show the linear correlation coefficients and the correlation coefficients squared. The latter column indicates the percentage increase of flexural strength that can be accounted for by delayed seasoning. Column 6 is the computed Z statistic for a null hypothesis of zero correlation. Column 7 is the 99.5 percent level of significance above which the null hypothesis of zero correlation (Column 6) must be rejected. In all cases, the null hypothesis of zero correlation must be rejected. Column 8 is the computed F statistic used to test the null hypothesis of linearity. Column 9 is the 95 percent level of significance with 9 and 44 degrees of freedom above which the null hypothesis of linearity (Column 8) must be rejected. In no case, can the assumption of linearity be rejected. The least squares estimate of best fit is given in Column 10.

A multiple range test comparing the slopes of each response is given in Table II-2. The slope of the notch-coated stringers was significantly greater than the slope of the nail-reinforced stringers at the point of initial failure. Neither slope, however, differed significantly from the slope of the control stringers. The slope of the nail-reinforced stringers at the point of ultimate load differed significantly from the slopes of the control and nail-reinforced stringers at the point of initial failure, but did not differ significantly from the slope of the notch-coated stringers.

The linear least squares estimate of each response is shown in Figure II-10. The load at initial failure of the nail-reinforced stringers, immediately after reinforcing was 11

Table II-1

Results of Flexure Tests on Modified Stringers

Column	1 Number of Tests	2 y Intercept	3 Slope	4 r	5 r^2	6 Test Statistic	7 Z	8 Test Statistic	9 $F_{9,44}$	10 Response
Control Stringers	55	1094	3.5	0.476	0.226	3.731	2.576	2.11	2.12	y=1094+3.5x
Notch-Coated Stringers	55	1143	4.8	0.603	0.363	5.031	2.576	1.57	2.12	y=1143+4.8x
Nail-Reinforced Stringers: Initial Failure	55	1212	2.1	0.391	0.153	2.982	2.576	0.65	2.12	y=1212+2.1x
Nail-Reinforced Stringers: Ultimate Failure	55	1373	6.3	0.643	0.413	5.504	2.576	1.38	2.12	y=1373+6.3x

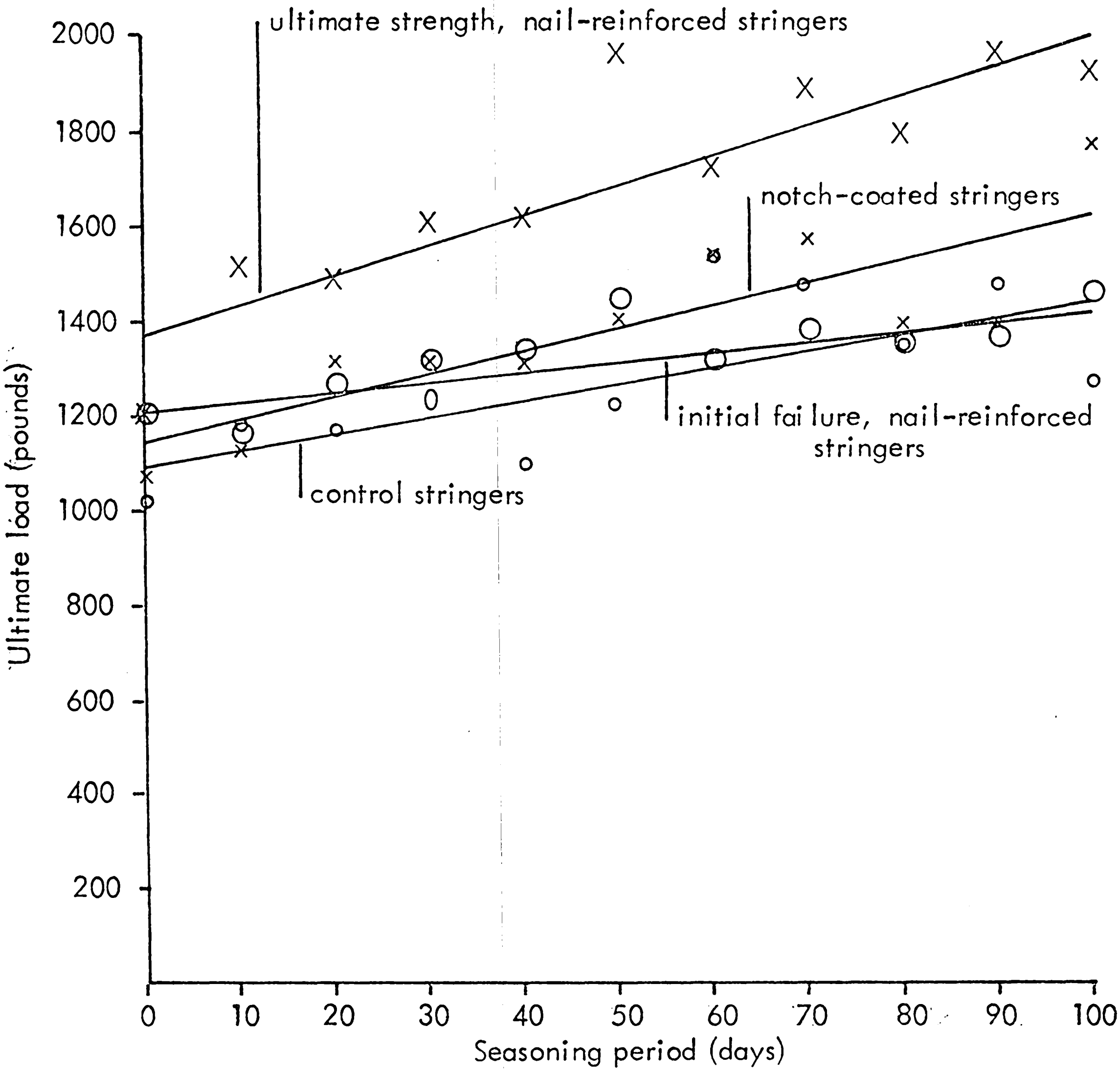
Table II-2

Multiple Range Test

Test Statistic Comparing Slopes of

Control Stringers	Notch-Coated Stringers	Nail-Reinforced Stringers: Initial Failure	Nail-Reinforced Stringers: Ultimate Load		$F_{2,212}$
3.5	4.8			1.07	4.60
3.5		2.1		1.27	4.60
3.5			6.3	4.97*	4.60
	4.8	2.1		4.69*	4.60
	4.8		6.3	1.42	4.60
		2.1	6.3	11.27*	4.60

* Indicates significance at the 90 percent level.



Average moisture content (percent o.d.)

Figure II-10. Flexural strength of modified notched pallet stringers.

X represents mean ultimate strength, nail-reinforced stringers.

O represents mean initial failure, nail-reinforced stringers.

x represents mean ultimate strength, notch-coated stringers.

o represents mean ultimate strength, control stringers.

percent greater than that of the control stringers. After 90-day seasoning, the load at initial failure approximated the control-stringer response. The ultimate strength of the nail-reinforced stringers, developing only after considerable center-span deflection, was considerably higher than that of either the control or notch-coated stringers.

The strength of the notch-coated stringers, tested immediately after reinforcing, was similar to that of the control stringers. Applying an adhesive to the notch surface retarded longitudinal moisture movement through the notch ends, and thus reduced stresses as could develop during seasoning. A reduction of internal stresses results in a stronger stringer. After a seasoning period of 100 days, the strength of the notch-coated stringers was 13 percent higher than that of either the control or nail-reinforced stringers. The slope of the notch-coated stringers differed significantly from the slope of the nail-reinforced stringers at the point of initial failure, although neither slope differed from the slope of the control stringers.

Conclusions

1. The stringer leading-edge impact-shear resistance, increased linearly with increasing notch radius. The impact-shear resistance of notches cut with a 1-inch end notch radius was approximately 12 percent higher than that of a similar square notch. No difference was observed between the response of machine-shaped notches and carefully manufactured band-sawn notches.

2. The slope of the load vs. deflection curve for all flexural samples was linear and independent of the notched-stringer geometry, rising to an abrupt failure when splits, extending from the inner notch end fillets, developed parallel to the grain of the stringers. A second degree polynomial best describes the flexural strength of notched pallet stringers vs. increasing end fillet radius. On the average, the response peaked at a notch end fillet radius approaching 1 inch. At this point, the flexural strength was increased 32 percent. Again, the response of the machine-shaped and band-sawn notched stringers did not differ significantly.

3. Nail-reinforcing, with the particular nail used, caused considerable checking of the stringer base adjacent to the nails. This checking might have been reduced if the nail head had not been countersunk into the base of the stringer. Nail-reinforcing increased the average immediate flexural strength of green pallet stringers. As the green nail-reinforced stringers seasoned, the advantages of such reinforcing were lost and the response approached that of the control stringers. However, the ultimate strength of nail-

reinforced stringers, reached after the center-span deflections exceeded 2 inches, was somewhat greater than either the control or notch-coated stringers. Notch-coating did not increase the immediate flexural strength of green pallet stringers. It increased, however, the average flexural strength of seasoned notched pallet stringers.

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Addenda: Richards, D.B. June, 1973. Effect of curved notches on wood strength. Paper to be presented at 27th Annual Meeting of the Forest Products Research Society in Anaheim, California, June 26. (Not reviewed by author.)

PART III

The Effect of Leadboard and Stringer Specific Gravity on the Impact Resistance of Wooden Pallets

Introduction

The majority of damages to reusable wooden pallets as a result of their handling by fork lift trucks, is found at the leading edges which include the leadboards and stringer ends (2, 5). The leadboards are pushed and pried from the pallets as lift-truck forks repeatedly strike against the upper leadboards. The design of the leading edge and the selection of the proper leadboard and stringer species are of prime importance.

The relationship between leading-edge impact resistance and leadboard and stringer specific gravity has not been established. It is known that high-density oak pallets outperform low-density yellow-poplar pallets of identical construction (8). This observation suggests a relationship between the field performance of wooden pallets and the specific gravity of the wood members.

The purpose of this study was to determine such a relationship. The leading-edge impact resistance of wooden pallets constructed from high and low-density hardwoods and softwoods was observed. Reusable stringer-type wooden pallets failed by impact shear causing nail bending withdrawal (5). Since the axial withdrawal resistance of wire nails pulled from wood samples is approximately proportional to the 5/2 power of their specific gravity (1), a second-order response model was postulated.

Test Materials

Six wood species, commonly used in North America to manufacture wooden pallets, were selected for this study. These species were hickory (0.77 average oven-dry specific gravity), red oak (0.64 average), soft maple (0.57 average), Douglas fir (0.50 average), southern pine (0.50 average), and aspen (0.40 average). Consequently, the average oven-dry specific gravity of these species range from 0.40 to 0.77 (1). The actual specific gravity values of the test material used in this study are given in Figures III-1 and 2. Twenty-four 1 x 4 x 40-inch leadboards and thirty-six 2 x 4 x 48-inch stringers were required of each species. This material was matched insofar as random-length, flat-sawn boards were selected. The leadboards and stringers were

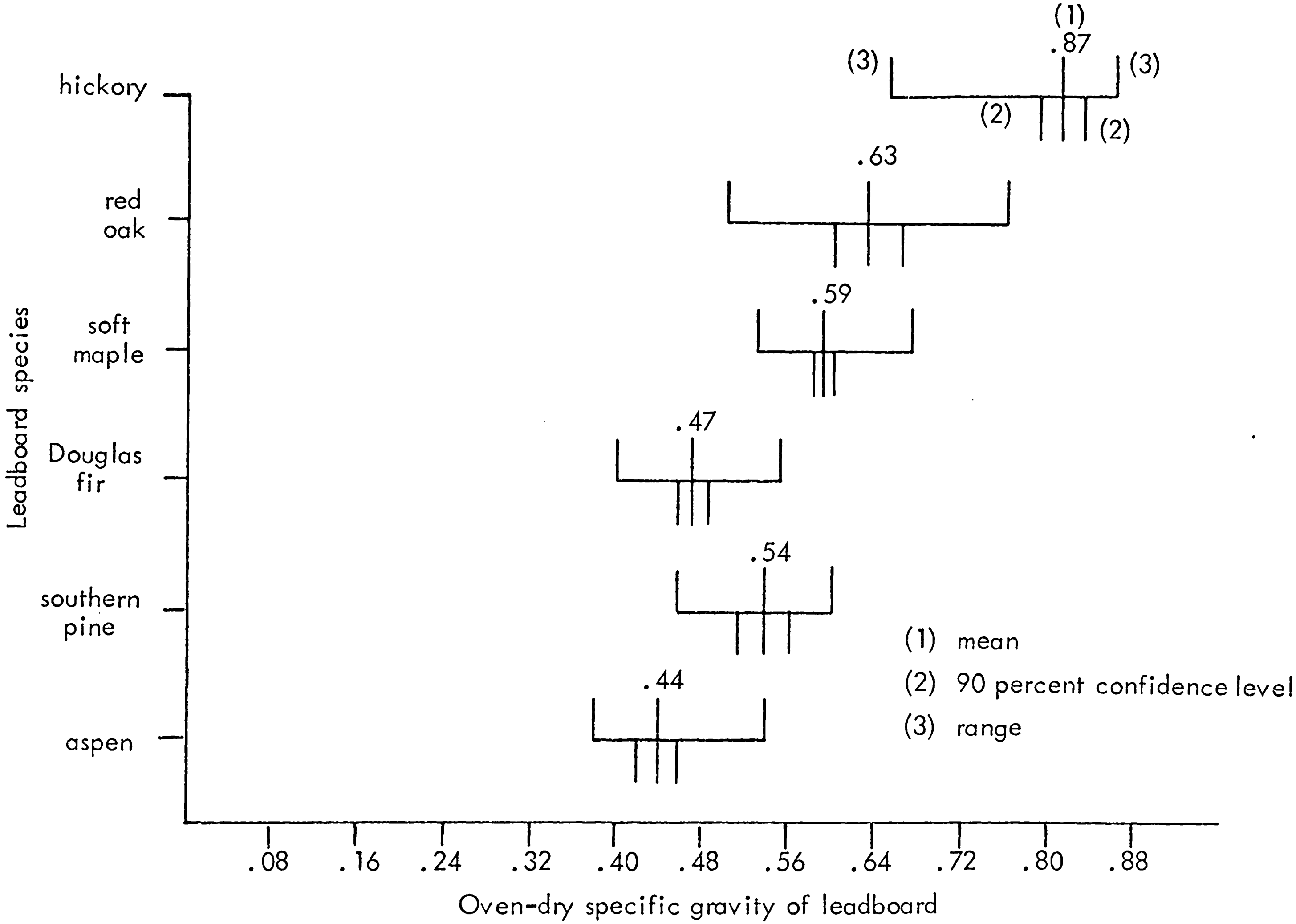

Figure III-1. Mean, confidence limit, and range of specific gravity of each of the six leadboard species.

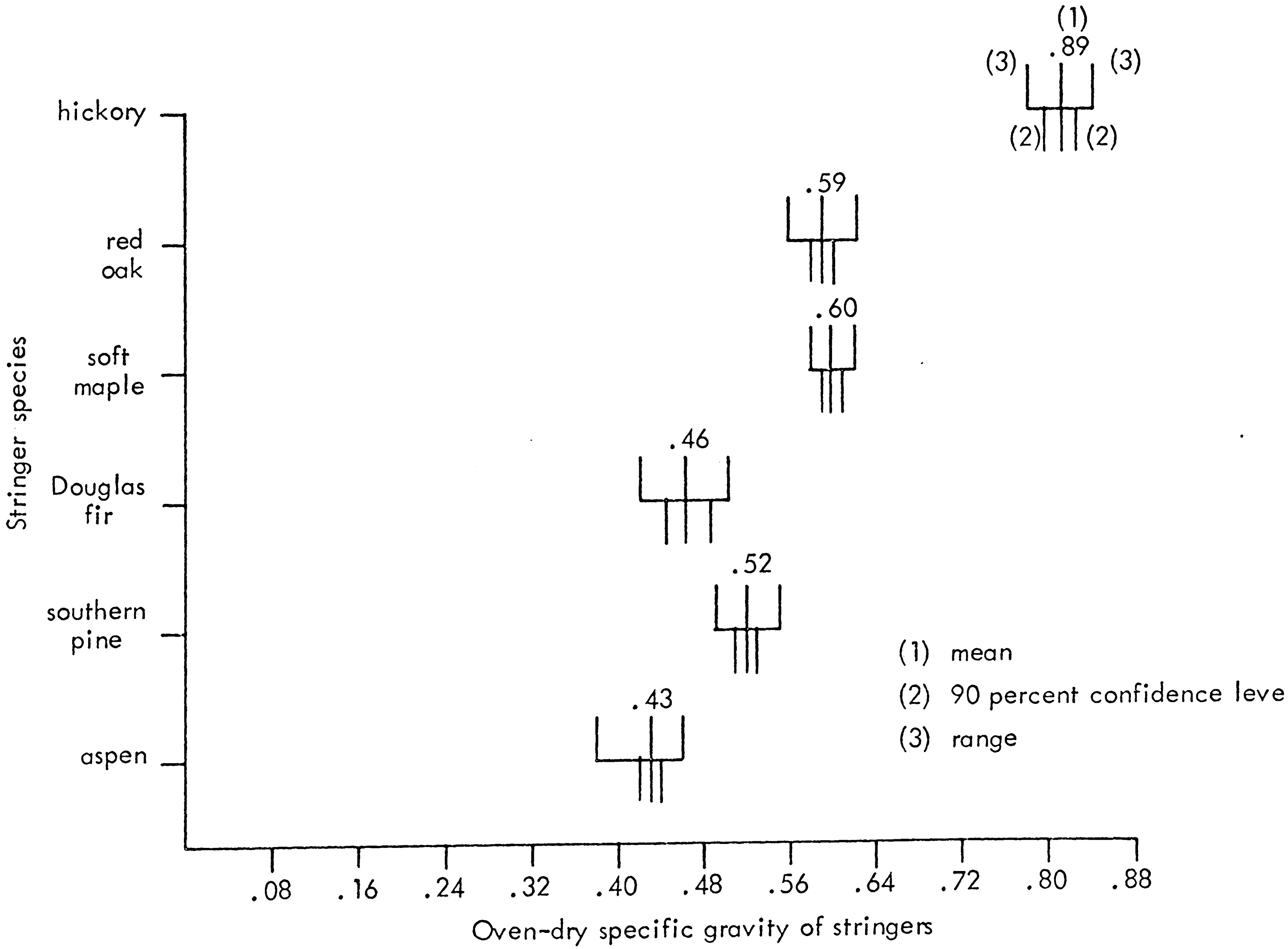

Figure III-2. Mean, confidence limit, and range of each of the stringer species.

sawn from relatively straight-grain and defect-free regions of the random-length boards. The selected leadboards and stringer ends conformed to the defect requirements of NWPCA hardwood and softwood specifications for premium-grade pallets (3, 4). The center region of the stringers was not examined and, therefore, certain below-grade defects, such as over-size tight knots, were not rejected.

The leadboards and stringers were dressed green to $\frac{3}{4} \times 5\frac{1}{2} \times 40$ and $1\frac{1}{2} \times 3\frac{1}{2} \times 48$ inches, respectively. The impact-resistance tests were performed with green leadboards and stringers, since most wooden pallets are manufactured with green lumber and are placed in service before having had time to season. Additionally, certain of the species might have required predrilling of both the leadboards and the stringers if they were to be assembled in seasoned condition. Since this is not a general requirement for all the species included in the tests, it was decided to perform them with green lumber. None of the leadboards or stringers were predrilled and such a variable was not introduced. The use of green lumber also eliminated the effects of any seasoning defects.

The nails used to fasten the leadboards to the stringers were 2 9/16 x 0.121-inch helically-threaded, hardened-steel nails (7). Each nail had five flutes, the crest diameter of which was 0.134 inches. Their thread angle was 60 degrees. Helical threading extended $1\frac{5}{8}$ inches from the diamond point (7). Important mechanical properties of these nails are given in Appendix V. All nails used came from the same box. Nails that had chipped or broken heads, were off-color, or otherwise obviously deviated from the specifications, were discarded. Since the nail properties influenced the test data, the findings need to be restricted to the fasteners used in this study.

Test Method

The leading-edge impact test was developed in 1971 at the Eastern Forest Products Laboratory of the Canadian Forestry Service (2, 5). The test simulates fork-lift entry. High-speed motion pictures show that the test reproduces typical pallet damage (Figure III-3). The American Society for Testing and Materials Committee D-10 on Packaging adopted this test in March, 1973, as an ASTM standard test method. A Modified Conbur impact testing device is required for this test. Therefore, the VPI&SU Conbur Impact Tester was designed and built as a part of this thesis project to compliment the pallet testing facilities of the Wood Research and Wood Construction Laboratory of the University's College of Architecture. This device is described in Appendix VI.

A THE TEST PALLET IS SHOWN RIDING UP THE FORKS ATTACHED TO THE CONBUR JUST PRIOR TO IMPACT.

B DURING IMPACT THE PALLET RIDES UP THE RADIUS OF CURVATURE AT THE BASE OF THE FORKS LIFTING THE PALLET FROM THE DECK OF THE DOLLY.

C THE SEVERE SHEARING FORCES DEVELOPED DURING IMPACT SPLITS AND PUSHES THE LEADBOARD BACK FROM THE LEADING EDGE.

D THE LEADBOARD IS BEING PRIED FROM THE STRINGERS DURING IMPACT. NOTE THE TWISTING OF THE LEADBOARD NAILS.

E FAILURE OF THE PALLET AFTER IMPACT.

Figure III-3. High speed motion pictures verify that the leading-edge impact test reproduces typical pallet damage. (Photo courtesy of Environment Canada. Eastern Forest Products Laboratory.)

The leading-edge impact test was used to determine the leading-edge impact resistance of 144 wooden pallets. A two-way classification was designed to compare all 36 leadboard and stringer combinations that can be derived from the six species available for study. Each combination was repeated four times and, therefore, each leadboard and stringer species was tested 24 times. The experimental design and test pallet numbers are given in Table III-1. The test pallets consisted of one parallel upper leadboard at each pallet end fastened to three parallel stringers. In addition, an auxillary deckboard was positioned between leadboards to serve as partial support of the weight box. In view of the possibility that stringer splitting might develop during testing, the pallets were made non-reversible. The leadboard and stringer selection was random. Each pallet was tested once at each end.

The test pallets were 48 x 40-inch rectangular prisms. The center stringer was placed equidistant from the outside stringers. All pallets were assembled in a jig. A nailing template was used to assure uniformity of the nailing pattern shown in Figure III-4. The leadboards were positioned on and fastened to the stringers in such a way that permissible defects were located along, or in the vicinity of, the leadboards' inside edges rather than the outside edges.

Each pallet was tested immediately after assembly. It was placed on the dolly of the Tester (Figure III-5). A dry, dressed, 1 x 8-inch southern pine board was fastened to the dolly under each stringer. The three boards served as friction boards and protected the top surface of the colly. A 32 x 40-inch 375-pound, steel weight box was positioned on the top deck of the pallet. The trailing edge of this box was angled over the trailing edge of the pallet in such a way that the kinetic energy associated with each impact was transferred directly to the stringers. This method of transferring the kinetic energy to the stringers does not damage the trailing-edge stringer ends. Each pallet positioned on the dolly was placed against a steel angle that was firmly fastened to the dolly and was parallel to the leading edge of the dolly. For this study, the angle iron was fastened $3\frac{3}{4}$ inches from the dolly's leading edge. Lateral stability was provided by four southern pine blocks nailed through the friction boards to the dolly surface. These blocks were positioned adjacent to each outside stringer near the leading and trailing pallet edges, to allow free longitudinal pallet movement during impact.

The forks were placed 21 inches center to center and positioned in such a way that the pallet entered the forks equidistant from each outside stringer.

Table III-1

Experimental Design and Number of Each Test Pallet

Stringer Species	Hickory	Red Oak	Soft Maple	Douglas Fir	Southern Pine	Aspen
	Test-Pallet Number (Deckboard Species)					
Hickory	1	25	49	73	97	121
	2	26	50	74	98	122
	3	27	51	75	99	123
	4	28	52	76	100	124
Red Oak	5	29	53	77	101	125
	6	30	54	78	102	126
	7	31	55	79	103	127
	8	32	56	80	104	128
Soft Maple	9	33	57	81	105	129
	10	34	58	82	106	130
	11	35	59	83	107	131
	12	36	60	84	108	132
Douglas Fir	13	37	61	85	109	133
	14	38	62	86	110	134
	15	39	63	87	111	135
	16	40	64	88	112	136
Southern Pine	17	41	65	89	113	137
	18	42	66	90	114	138
	19	43	67	91	115	139
	20	44	68	92	116	140
Aspen	21	45	69	93	117	141
	22	46	70	94	118	142
	23	47	71	95	119	143
	24	48	72	96	120	144

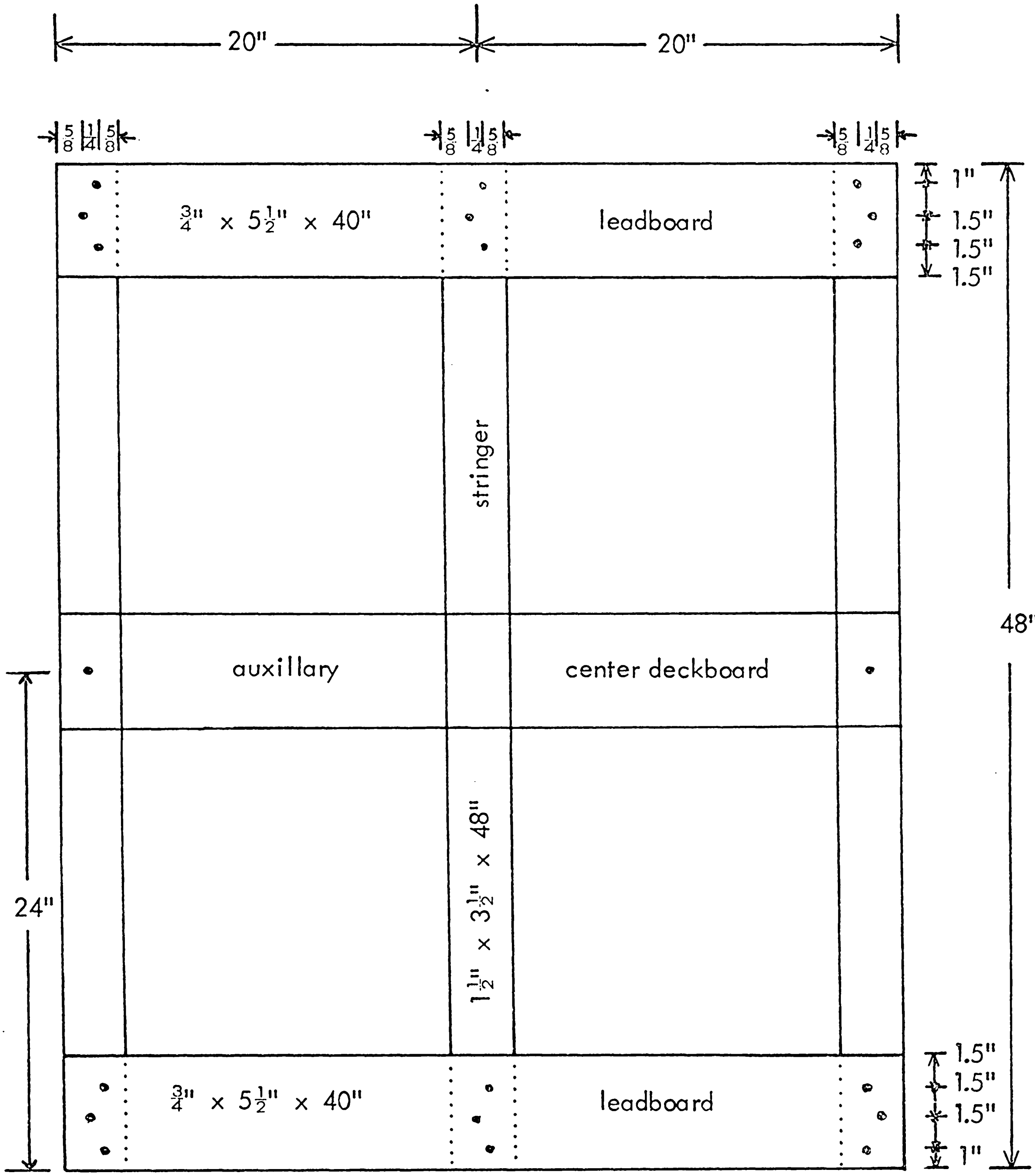

Figure III-4. Pallet dimensions and nailing pattern of each test pallet.

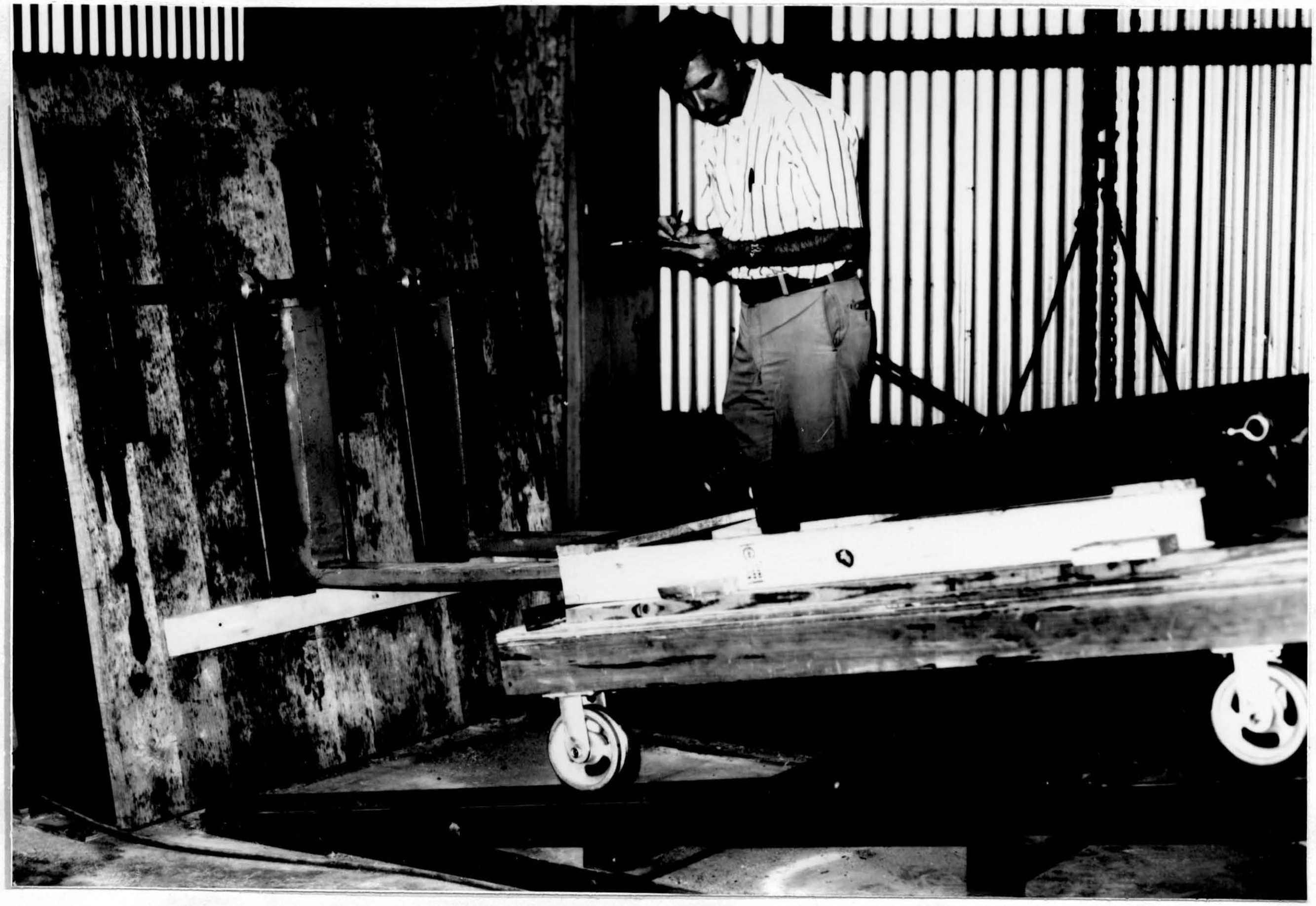

Figure III-5. The VPI&SU Conbur Impact Tester. The operator is observing the leading-edge impact resistance of the wooden pallet which was located by the steel angle, fastened to the dolly top in such a way that the leading edge of the pallet was $3\frac{3}{4}$" from the leading edge of the dolly.

In the field, the forks of a lift truck seldom enter a pallet parallel to its deck. The forks attached to the Tester's backstop were adjusted in such a way that the pallet struck, and rode up the tines of the forks during its last 8 inches of travel (Figure III-6). This was accomplished by angling the forks vertically downward 4 degrees from the direction of travel. This angling of the fork tines simulates the pushing and prying action of lift trucks.

Each pallet travelled down the inclined track striking the heels of the forks after a travel of 30 inches, measured along the plane parallel to the inclined track. The pallet was placed on the dolly in such a way that the pallet struck the forks before the dolly struck the rigid backstop. The travel distance of the dolly before striking the backstop was $33\frac{1}{4}$ inches. The pallet was repositioned against the angle iron after each impact and the test was repeated until failure occurred. Failure was considered to have taken place when the leadboard was torn from two of the three stringers.

The oven-dry specific gravity of each leadboard and stringer was determined by the mercury-immersion method (ASTM D 2395). The average specific gravity of the three stringers in each pallet was determined by calculating the average specific gravity of the three stringers. The moisture content of a random sampling of the pallet lumber was determined by the oven-dry method to confirm that the moisture content exceeded fiber saturation.

Test Results

The number of impacts required to cause failure and the specific gravity of each leadboard and stringer are given in Appendix VII.

One of the 1296 nails, the trailing edge nail fastening the leadboard to the center stringer of Pallet 7, sheared at the leadboard-stringer interface. All other nails bent away from the leading edge. The mode of failure of the majority of the test pallets was similar. It was predictable. Nail splits developed at the leadboard ends through the nail locations. The leadboards lifted from the center stringer. Splitting of the leadboards did not result in imminent pallet failure as defined previously. For example, nail splits developed in Pallet 30 after 7 impacts; yet, the pallet did not fail until after 45 impacts. Similarly, nail splits developed after 2 impacts in Pallet 29; yet, failure did not occur until after 50 impacts.

Pallet failure could be predicted. In the majority of the pallets tested, the leadboard lifted from the center stringer. This phenomenon occurred 2 to 10 impacts prior to

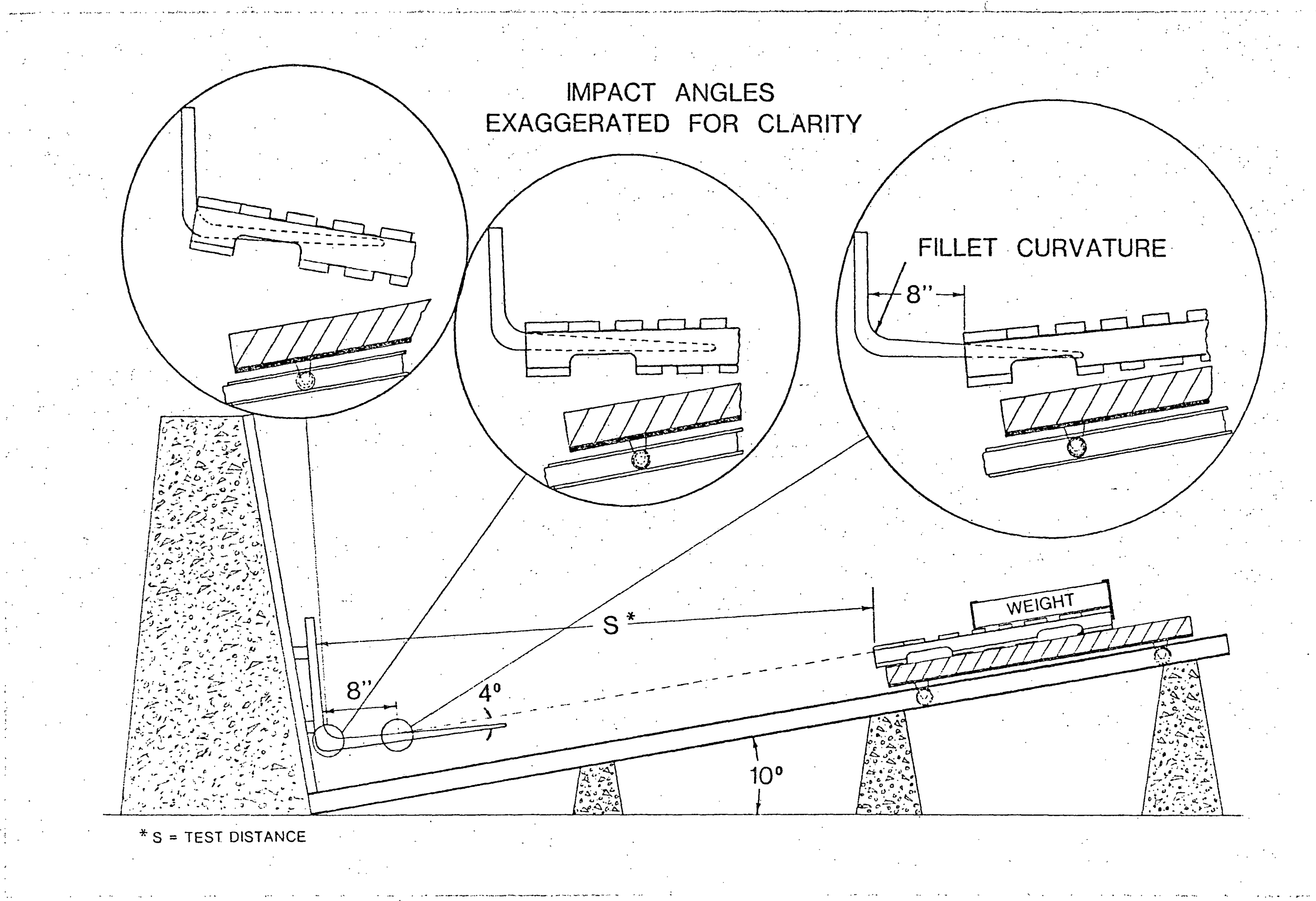

Figure III-6. Schematic diagram of inclined impact test. Note how the pallet rides up the forks prior to impact, followed by a pronounced lifting of the leading edge as it contacts the tines of the forks.

failure. This lifting of the leadboard from the center stringer was noted in every pallet for which normal failure was observed.

Failure of the test pallets occurred in the following modes: the nail shanks pulled out of the stringers and/or the nail heads pulled through the leadboards. If a high-density leadboard was nailed to low-density stringers, failure took place as a result of nail-shank pull-out. If a low-density leadboard was fastened to high-density stringers, failure took place as a result of nail-head pull-through at the outside stringers where nail splits had developed in the leadboards.

Deviations from the normal failure pattern were striking. Except in southern pine/hickory Pallets 99 and 100, all of the hickory stringers split during nailing possibly because of the 1-inch distance between lead nail and stringer end. These test pallets failed prematurely by nail-shank pull-out. Brash failures, occurred often (6). Such failures developed suddenly in the leadboards of Pallets 5, 8, 32, 39, 40, 57, 62, 63, 70, and 107. The specific gravity of the leadboard was, in most of these pallets, below the species average. The hickory leadboard of Pallet 6 was straight-grained and completely free of defects, such as knots and wane. The pith encased along this board was located near its center and caused failure after 5 impacts.

The failure resistance of aspen/maple Pallet 132 was unexpectedly high. This pallet failed after 27 impacts, whereas the other three pallets failed after 4, 6, and 14 impacts. Nail head pull-through was resisted by the leading nail driven into the center stringer. The pallet finally failed by full-length leadboard splitting through this nail location. Except for the previously described abnormal failures, this was the only other failure that could not be predicted. When the leadboard did not lift from the center stringer, the impact resistance was increased significantly.

The specifications of the National Wooden Pallet and Container Association permit small, tight knots along the trailing edge of the leadboard (3, 4). Pallet 40 contained a 1-inch tight knot along the trailing edge of the leadboard. Although a knot of this size is permitted, the pallet failed after four impacts (Figure III-7).

The test data were analyzed twice. The first analysis included all of the test results. Those pallets which deviated in their failures from the norm were excluded from the second analysis.

Table III-2 presents the average numbers of impacts to failure for each stringer and leadboard combination. All of the test data are included in this Table. Table III-3

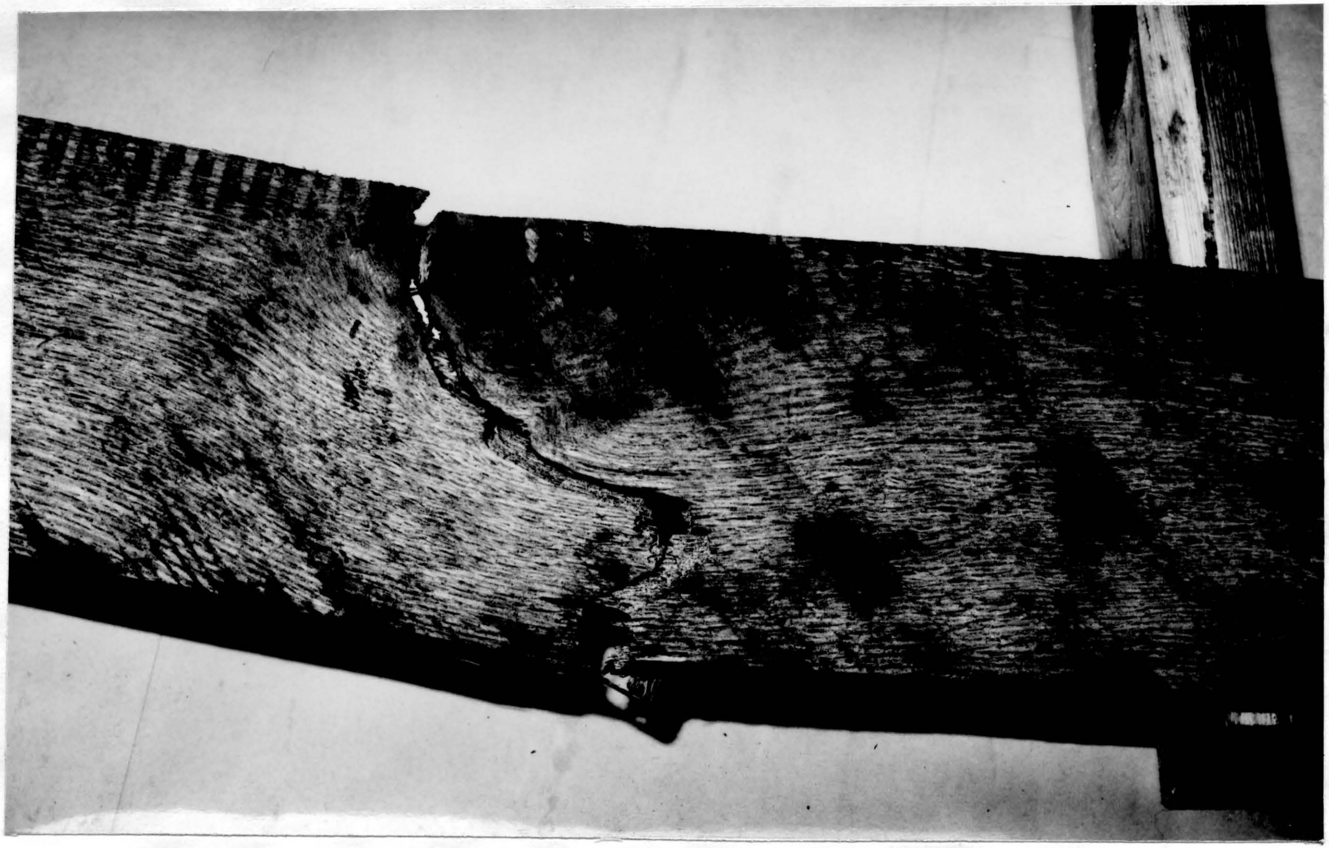

Figure III-7. A permissible, tight knot located along the trailing edge of this oak leadboard caused failure after only 4 impacts.

Table III-2

Average Number of Impacts Causing Failure of All Test Pallets

Stringer Species	Deckboard Species: Hickory	Red Oak	Soft Maple	Douglas Fir	Southern Pine	Aspen
Hickory	27	5	5	6	25	4
Red Oak	38	37	14	11	12	6
Soft Maple	93	48	21	10	10	13
Douglas Fir	13	9	6	8	9	5
Southern Pine	5	5	4	4	8	4
Aspen	4	4	3	3	4	3

Note: The number of impacts causing failure can be converted to energy by multiplying the numbers by 163.

Table III-3

Analysis of Impact Tests for All Test Pallets

ANOVA

Source	DF	SS	MS	Test Statistic	$F_{(.999), 6, 138}$
Regression	6	47334	7889	32.6	4.04
Error	138	33414	242		
Total	144	80748			

Coefficient	Test Statistic	$T_{.99, 138}$
$b_1 = -294$	2.77	2.36
$b_2 = 431$	4.11	2.36
$b_1^2 = 188$	2.46	2.36
$b_2^2 = -420$	5.30	2.36
$b_{12} = 213$	2.88	2.36

Response

$$Y = -55 - 294x_1 + 431x_2 + 188x_1^2 - 420x_2^2 + 213x_1x_2$$

Multiple Correlation

$R = .766$

Stationary Point

$x_1 = .430$

$x_2 = .622$

Where

x_1 = leadboard specific gravity.

x_2 = stringer specific gravity.

contains an analysis of variance used to calculate, by the method of least squares, a second-order response function that can be used to calculate the expected impact resistance of any leadboard and stringer combination knowing the leadboard and stringer specific gravity. Since all of the data are included, there are 6 degrees of freedom due to regression and 138 degrees of freedom due to error. The expected response, the multiple regression coefficient, and the stationary point are also given in Table III-3.

The expected response is highly significant at the 99.9 percent level. The linear, quadratic, and cross-product coefficients are significant and the regression is, therefore, considered valid. The intercept does not differ significantly from zero. The square of the multiple correlation coefficient indicates that 58.7 percent of any change in the expected response Y can be explained by changes in the leadboard and stringer specific gravity.

The slope of the expected response surface is zero at the stationary point located near the edge of the experimental design. The regression coefficients suggest that a wooden pallet's leading-edge resistance can be best achieved by increasing the leadboard specific gravity. An increase of stringer specific gravity will not necessarily increase the expected response unless the increase of stringer specific gravity is accompanied by an increase of leadboard specific gravity. The split hickory stringers, included in this analysis may have altered the experimental response.

Tables III-4 and III-5 provide similar information as Tables III-2 and III-3, respectively, except that those hickory stringers that split during nailing and those test pallets that failed abnormally were excluded from the second analysis. Since 34 of the test results were excluded, there were 104 degrees of freedom due to error.

Table III-5 confirms what the table of averages (Table III-4) indicates. The postulated model is highly significant at the 99.9 percent level. The interraction or cross-product coefficient and the linear and quadratic coefficients of the leadboard specific gravity are also significant at the 99 percent level. The quadratic coefficient of the stringer specific gravity appears to be redundent. The intercept, lying outside the experimental range, differs from zero. There is very good correlation between x_1, x_2, and the expected response Y. The correlation coefficient squared indicates that 81.5 percent of any change in the response Y can be explained by changes in the leadboard and stringer specific gravity. The correlation coefficient of 0.903 (Table III-5) indicates that the species effect is insignificant for the six wood species tested.

Table III-4

Average Number of Impacts Causing Failure of Test Pallets with Normal Failures

Stringer Species	Deckboard Species: Hickory	Red Oak	Soft Maple	Douglas Fir	Southern Pine	Aspen
Hickory	--	--	--	--	42 (2)	--
Red Oak	100 (1)*	46 (3)	14 (4)	11 (4)	12 (4)	6 (4)
Soft Maple	93 (4)	48 (4)	26 (3)	10 (4)	12 (3)	8 (3)
Douglas Fir	13 (4)	14 (2)	9 (2)	8 (4)	9 (4)	5 (4)
Southern Pine	5 (4)	5 (4)	4 (4)	4 (4)	8 (4)	4 (4)
Aspen	4 (4)	4 (4)	3 (3)	3 (4)	4 (4)	3 (4)

* numbers in parenthesis indicate number of tests included.

Note: The number of impacts causing failure can be converted to energy (foot-pounds) by multiplying the numbers by 163.

Table III-5

Analysis of Impact Tests for Selected Test Pallets

ANOVA

Source	DF	SS	MS	Test Statistic	$F_{(.999), 6, 104}$
Regression	6	61159	10193	76.41	4.05
Error	104	13874	133		
Total	110	75033			

Coefficient	Test Statistic	$T_{.99, 104}$
$b_1 = -792$	11.05	2.36
$b_2 = -415$	6.48	2.36
$b_1^2 = 199$	4.25	2.36
$b_2^2 = -117$	1.04	2.36
$b_{12} = 1205$	10.07	2.36

Response

$$Y = 288 - 792x_1 - 415x_2 + 199x_1^2 - 177x_2^2 + 1205x_1x_2$$

Multiple Correlation

$R = .903$

Stationary Point

$x_1 = .444$

$x_2 = .511$

Where

x_1 = leadboard specific gravity.

x_2 = stringer specific gravity.

The stationary point is again located near the edge of the experimental region. The regression coefficients again suggests that a wooden pallet's leading edge impact resistance is most effectively achieved, at any point within the experimental region, by increasing the leadboard specific gravity. Leading edge impact resistance is highly dependent on both leadboard and stringer specific gravity.

The leading edge impact resistance can be expressed in terms of kinetic energy. The transformation requires that the expected response Y be multiplied by a single constant KE

where

$$\begin{aligned} KE &= PE \\ &= w \times \frac{s}{12} \sin 10^{\circ} \\ &= \frac{ws}{69} \\ &= 163 \end{aligned}$$

where

w is the bearing load on the pallet

s is the free travel distance down the inclined track in inches

The expression KE(Y) describes the experimental response in terms of foot-pounds of energy required to damage a wooden pallet's leading edge.

Conclusions

1. Leading-edge failures are predominantly the result of nail-head pull-through if low-density leadboards are nailed to high-density stringers.
2. Leading-edge failures are predominantly the result of nail-shank pull-out if high-density leadboards are nailed to low-density stringers.
3. Leading-edge failures are a combination of nail-shank pull-out and nail-head pull-through if leadboards and stringers are of like species, or woods of similar specific gravity. In these instances, the nail shanks pull out of the center stringer and the nail heads pull through splits which develop through nail locations at the leadboard ends.
4. Splits, which develop through nail locations at the leadboard ends do not result in an imminent failure of wooden pallets.
5. Failure is always preceeded by a lifting of the leadboard from the center stringer. None of the test pallets failed normally unless this phenomenon had occurred. Therefore, the leading-edge impact resistance may be significantly improved if this lifting phenomenon is restrained. This may be accomplished by one supplementary nail driven through the leadboard into the center stringer.
6. Small tight knots, even if located along the trailing edge of a leadboard, and their accompanying localized cross-grain can significantly lower the leading-edge impact resistance.
7. A second-order response function accurately describes the effect of specific gravity on the leading-edge impact resistance of wooden pallets.
8. Specific gravity, regardless of wood species, determines the leading-edge impact resistance.
9. The leading-edge impact resistance increases more rapidly if the leadboard, rather than the stringer, specific gravity is increased.
10. An increase of the stringer specific gravity may, but does not necessarily, increase the leading-edge impact resistance unless the increase in the stringer specific gravity is accompanied by an increase in the leadboard specific gravity.
11. High-density stringers, such as hickory, may split during assembly. Split stringers significantly reduce the leading-edge impact resistance.

12. The leading-edge impact resistance is highly dependent on both the leadboard and stringer specific gravity.

13. The leading-edge impact resistance can be maximized if the most dense lumber available is used for leadboards and the less dense lumber is used for stringers.

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APPENDIX I

Energy Relationships Used in Shear Calculations

Appendix I

Energy Relationship Used in Shear Calculations

The total work required to shear off the foot end of a notched pallet stringer may be described as the kinetic and potential energy loss of the free fall dropping head during impact.

FORMULAE

V_1 = velocity of dropping head at impact in in./sec.

t_1 = initial time at impact in sec.

h_1 = height of dropping head at t_1 in inches.

V_2 = velocity of dropping weight immediately after impact in in./sec.

t_2 = time at V_2 in sec.

Δt = $t_2 - t_1$.

h_2 = height of dropping head at t_2 in inches.

a = acceleration in in./sec.^{2}

G = gravitational constant = 386.4 in./sec.^{2}

g = a/G = acceleration expressed as units of G.

w = weight of dropping head in lb.

m = w/G = mass of dropping head in pdl.

E_L = energy loss of loading head during impact in in.-lb.

= total work required to shear off the foot end of a stringer.

KE = kinetic energy in in.-lb.

PE = potential energy in in.-lb.

Energy Relationships

Since

KE before impact (time t_1) = $1/2\, m V_1^2$; PE before impact = $m G h_1$

KE after impact (time t_2) = $1/2\, m V_2^2$; PE after impact = $m G h_2$

then

$$E_L = 1/2\, m V_1^2 + mGh_1 - (1/2\, m V_2^2 + mGh_2)$$

$$E_L = 1/2\, w/G(V_1 - V_2)\ (V_1 + V_2) + w(h_1 - h_2)$$

Now

$$V_2 = V_1 + \int_{t_1}^{t_2} (G - a)\ dt \quad (1)$$

$$V_2 = V_1 + G\Delta t - GA$$

where

$$A = \int_{t_2}^{t_1} g\,dt$$

therefore

$$E_L = 1/2\, w/G\ [\ V_1 - (V_1 + G\Delta t - GA)][\ V_1 + (V_1 + G\Delta t - GA)] + w(h_1 - h_2)$$

or

$$E_L = w(V_1A + G\Delta tA - [G/2]A^2 - V_1\Delta t - [G/2]\Delta t^2) + w(h_1 - h_2) \quad (2)$$

---

(1) The term (G − a) is required because of a 1 G calibration error associated with piezoelectric accelerometers. Sinusoidal accelerations of ± 1 G as observed on a cathode ray tube are, in fact, absolute acceleration of 0. −2 G.

(2) The terms $G/2A^2$, and $w(h_1 - h_2)$ are insignificant and were not included in the calculations.

APPENDIX II

Detailed Shear Test Data

Appendix Table II-1

Work to Shear Foot of Stringers having Machine-Shaped Notches (inch - pounds)

Notch Radius (inches) (0.00" to 1.50")

Replication	0.00	0.25	0.50	1.00	1.25	1.50
1	468	495	638	712	921	708
2	386	622	636	615	950	833
3	394	640	562	698	776	810
4	438	649	618	612	948	891
5	457	566	463	672	804	722
6	472	623	655	641	773	674
7	610	591	618	748	806	808
8	601	564	736	833	785	862
9	629	505	699	659	806	742
10	692	663	601	684	832	787
11	731	664	617	584	804	669
12	692	579	584	690	641	764
13	643	604	562	739	900	782
14	587	602	701	705	751	685
15	607	643	649	758	661	795
16	632	571	525	602	824	734
17	604	579	685	799	811	768
18	518	652	620	601	908	955
19	589	606	510	844	804	856
20	422	503	554	809	859	996
21	644	573	671	616	747	735
22	549	623	725	774	838	820
23	511	621	630	667	988	827
24	627	797	540	861	1115	948
25	647	569	445	814	913	784
26	538	500	666	783	1005	765
27	740	596	457	844	705	862
28	630	596	502	866	794	837
29	567	617	680	785	832	926
30	497	629	505	841	814	828
31	651	502	662	965	966	850
32	551	612	662	887	836	877
33	566	629	521	713	805	805
34	527	784	591	633	899	777
35	640	629	514	694	706	750
36	521	636	794	756	830	977
MEAN	572	606	605	736	838	811
STANDARD DEVIATION	217	228	229	278	315	305

Appendix Table II-2

Work to Shear Foot of Stringers
having Band-Sawn Notches
(inch - pounds)

Replication	Notch Radius (inches) (0.00" to 1.50")					
	0.00	0.25	0.50	1.00	1.25	1.50
1	565	665	616	703	797	883
2	560	586	546	667	805	916
3	477	564	567	711	461	785
4	566	539	629	625	638	884
5	536	652	726	695	871	797
6	519	667	601	671	747	782
7	497	587	713	733	768	862
8	435	434	674	717	727	760
9	514	617	491	681	798	893
10	548	641	733	824	812	867
11	544	587	683	804	918	834
12	477	488	653	773	1003	755
13	436	483	572	744	680	852
14	462	523	503	638	842	837
15	396	484	567	566	860	823
16	507	490	608	827	920	807
17	432	579	708	768	859	900
18	501	574	667	800	755	887
19	463	567	649	703	660	853
20	495	547	665	662	682	814
21	521	591	702	831	696	840
22	461	539	587	541	774	626
23	413	652	828	812	688	801
24	436	762	721	646	838	747
25	464	559	660	827	765	824
26	656	669	936	628	810	712
27	463	625	768	863	594	806
28	501	605	715	515	708	816
29	450	622	655	661	887	914
30	488	626	757	546	852	811
31	515	583	671	577	780	1020
32	574	595	723	836	800	759
33	558	751	616	527	867	740
34	602	527	788	522	805	736
35	548	521	634	706	699	809
36	593	618	714	841	678	631
MEAN	505	587	668	700	773	816
STANDARD DEVIATION	190	221	252	265	292	306

APPENDIX III

Detailed Flexural Test Data

Appendix Table III-1

Ultimate Flexural Strength of Stringers having Machine-Shaped Notches (pounds)

Replication	Notch Radius (inches) (0.00" to 1.50")					
	0.00	0.25	0.50	1.00	1.25	1.50
1	935	920	1280	1060	1220	1070
2	820	850	1015	1130	1235	1200
3	1080	680	1220	985	1210	1290
4	1165	980	1220	915	1240	1370
5	850	780	1355	1320	1090	1120
6	745	1045	1080	1300	1150	1410
7	680	925	1180	950	1220	1170
8	670	970	1070	1025	1160	1020
9	1100	1000	1220	1170	1510	1115
10	920	800	940	1115	1340	1225
MEAN	897	895	1158	1097	1238	1199
STANDARD DEVIATION	344	339	438	416	467	453

Appendix Table III-2

Ultimate Flexural Strength of Stringers having Band-Sawn Notches (pounds)

Replication	Notch Radius (inches) (0.00" to 1.50")					
	0.00	0.25	0.50	1.00	1.25	1.50
1	780	790	850	1175	1280	930
2	690	1310	1155	1200	1280	1230
3	970	800	1060	1160	1080	1240
4	920	1000	885	1000	1440	1175
5	875	1085	1040	790	1140	1040
6	735	720	1220	1150	1170	980
7	970	1280	1080	1145	1095	1310
8	1020	1392	1115	1145	1140	1200
9	840	640	1008	1280	1255	860
10	920	1000	1092	1120	880	900
MEAN	872	1002	1051	1117	1176	1087
STANDARD DEVIATION	330	390	397	423	446	413

APPENDIX IV

Detailed Test Data for
Modified Stringers

Appendix Table IV-1

Ultimate Flexural Strength (pounds) of Control Stringers
for Given Seasoning Periods (days)

Replication	Days										
	0	10	20	31	40	49	60	70	80	90	101
1	970	1032	970	950	1180	1170	1930	1260	1500	1580	1180
2	1230	1160	1220	1440	1060	1350	1570	1570	1480	1710	890
3	980	1390	1240	1330	1220	1320	1325	1280	1380	1140	1370
4	900	1000	1220	1325	850	1050	1490	1490	1240	1170	1365
5	1016	1285	1190	1030	1165	1210	1405	1760	1100	1770	1525
MEAN	1019	1173	1168	1215	1095	1220	1544	1472	1340	1474	1266
STANDARD DEVIATION	298	343	340	357	320	355	452	431	391	435	373

Appendix Table IV-2

Ultimate Flexural Strength (pounds) of Notch-Coated Stringers
for Given Seasoning Periods (days)

Replication	Days										
	0	10	20	31	40	49	60	70	80	90	101
1	1070	1310	1430	1460	1265	1290	1690	1455	1220	1515	1970
2	1200	1084	1290	1350	1540	1440	1670	1830	1270	1485	1920
3	910	1220	1220	1210	1305	1595	1080	1770	1050	1470	1540
4	1008	836	1370	1390	1195	1220	1470	1320	1620	940	1600
5	1244	1220	1290	1200	1280	1500	1790	1485	1770	1520	1790
MEAN	1086	1134	1320	1322	1317	1409	1540	1572	1386	1386	1764
STANDARD DEVIATION	317	333	384	385	384	411	453	460	410	408	514

Appendix Table IV-3

Load at Initial Flexural Failure (pounds) of Nail-Reinforced Stringers for Given Seasoning Periods (days)

Replication	Days										
	0	10	20	31	40	49	60	70	80	90	101
1	1120	1240	1500	1355	1510	1600	1030	1445	1300	1360	1580
2	1060	1130	1630	1410	1380	1560	1170	1250	1250	1450	1450
3	1390	1030	960	1240	1470	1410	1640	1280	1420	1250	1550
4	1210	1080	1155	1320	1385	1370	1220	1540	1260	1500	1250
5	1208	1208	1060	1245	920	1270	1460	1320	1425	1200	1425
MEAN	1198	1152	1261	1314	1333	1442	1304	1367	1331	1352	1451
STANDARD DEVIATION	349	335	374	382	392	420	384	398	387	394	422

Appendix Table IV-4

Ultimate Flexural Strength (pounds) of Nail-Reinforced Stringers for Given Seasoning Periods (days)

Replication	Days										
	0	10	20	31	40	49	60	70	80	90	101
1	1120	1400	1820	1700	1960	1980	1340	1970	1700	2300	1980
2	1060	1540	1630	1600	1700	1950	1680	1450	1720	2350	1730
3	1390	1360	1400	1400	1800	2000	2125	2250	1920	1750	2200
4	1210	1570	1155	1660	1200	2000	1520	2050	1980	1920	1750
5	1208	1645	1350	1600	1385	1870	1940	1675	1600	1460	1900
MEAN	1198	1503	1471	1592	1609	1960	1721	1879	1784	1956	1912
STANDARD DEVIATION	349	437	433	463	474	569	507	552	519	577	557

APPENDIX V

Mechanical Properties of Nails Used to Assemble Test Pallets

Appendix Table V-1

MIBANT Test Results (degrees)

Repli-cation	Degrees	Repli-cation	Degrees	Repli-cation	Degrees	Repli-cation	Degrees	Repli-cation	Degrees
1	19	6	20	11	20	16	20	21	20
2	20	7	20	12	20	17	21	22	20
3	20	8	21	13	20	18	21	23	20
4	20	9	19	14	20	19	20	24	18
5	18	10	20	15	19	20	20	25	20

MEAN = 20
STANDARD DEVIATION = 0.76

Number of partial failures = 0
Number of total failures = 0

Appendix Table V-2

Deckboard-Stringer Separation Resistance
Immediate Withdrawal Resistance (pounds)
from Red Oak

Replication	Withdrawal Resistance	Replication	Withdrawal Resistance
1	630	4	634
2	675	5	660
3	571	6	665

MEAN = 639
STANDARD DEVIATION = 38

stringer specific gravity = 0.62
stringer moisture content = 77%
depth of penetration = $1\frac{3}{4}$"

Appendix Table V-3

Deckboard-Stringer Separation Resistance
Immediate Head Pull-Through Resistance (pounds)
from Red Oak

Replication	Withdrawal Resistance	Replication	Withdrawal Resistance
1	552	4	570
2	568	5	625
3	611	6	600

MEAN = 588
STANDARD DEVIATION = 20

deckboard specific gravity = 0.57
deckboard moisture content = 58%
deckboard thickness = 13/16"

APPENDIX VI

The VPI&SU Conbur Impact Tester

The Conbur Impact Tester was originally developed by the Freight Container Bureau of the Association of American Railroads. Its original purpose was to simulate rail-car shunting shocks. It was used to design containers handled by American railroads.

The device consists of a dolly which rolls freely down two parallel tracks inclined 10 degrees to the horizontal. The test container is placed on the dolly in such a way that the forward leading edge of the container is positioned at or beyond the forward leading edge of the dolly. A simulated shunting or coupling shock is obtained when the free-rolling dolly and test container strike a rigid backstop. This rigid backstop is securely fixed at the base of and is perpendicular to the inclined track.

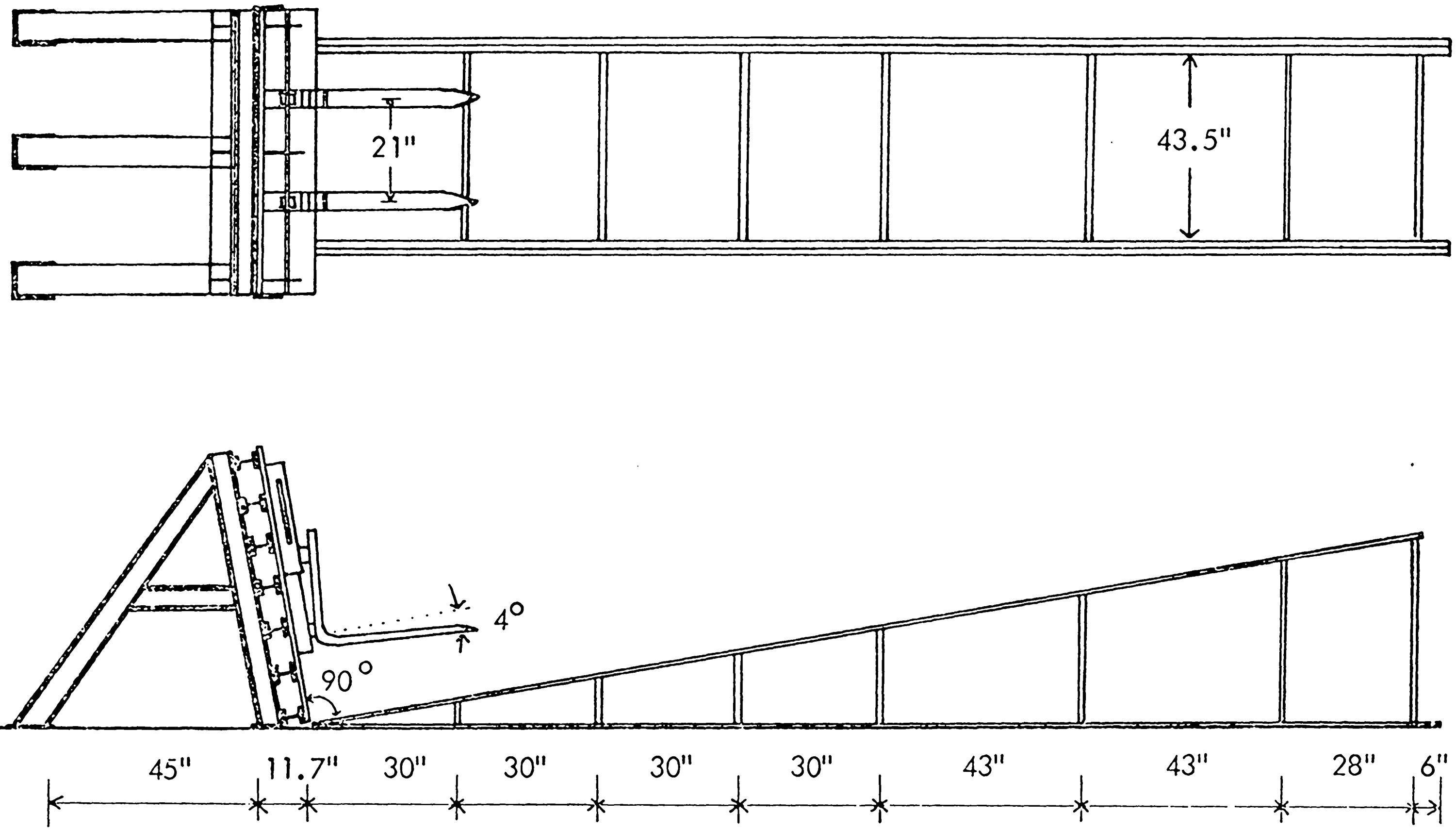
This device was modified for pallet testing purposes. The modified inclined impact test more accurately simulates the previously described pallet damage. Two forks of the kind used on a fork-lift truck are securely affixed to the rigid backstop of the device. The test is performed by running a loaded pallet into the forks, thus simulating actual fork-lift hazards. The velocity at impact can be controlled by fixing the travel distance of the dolly down the inclined track. The velocity of the test pallet at impact, in miles per hour, is approximately two-thirds the travel distance, in feet.

The forks of a lift truck seldom enter a pallet parallel to its deck. Therefore, the forks attached to the backstop are adjusted in such a way that the pallet strikes, and rides up, the tines during its last 8 inches of travel. This is accomplished by angling the tines vertically downward 4 degrees from the direction of travel and by appropriately adjusting the fork height.

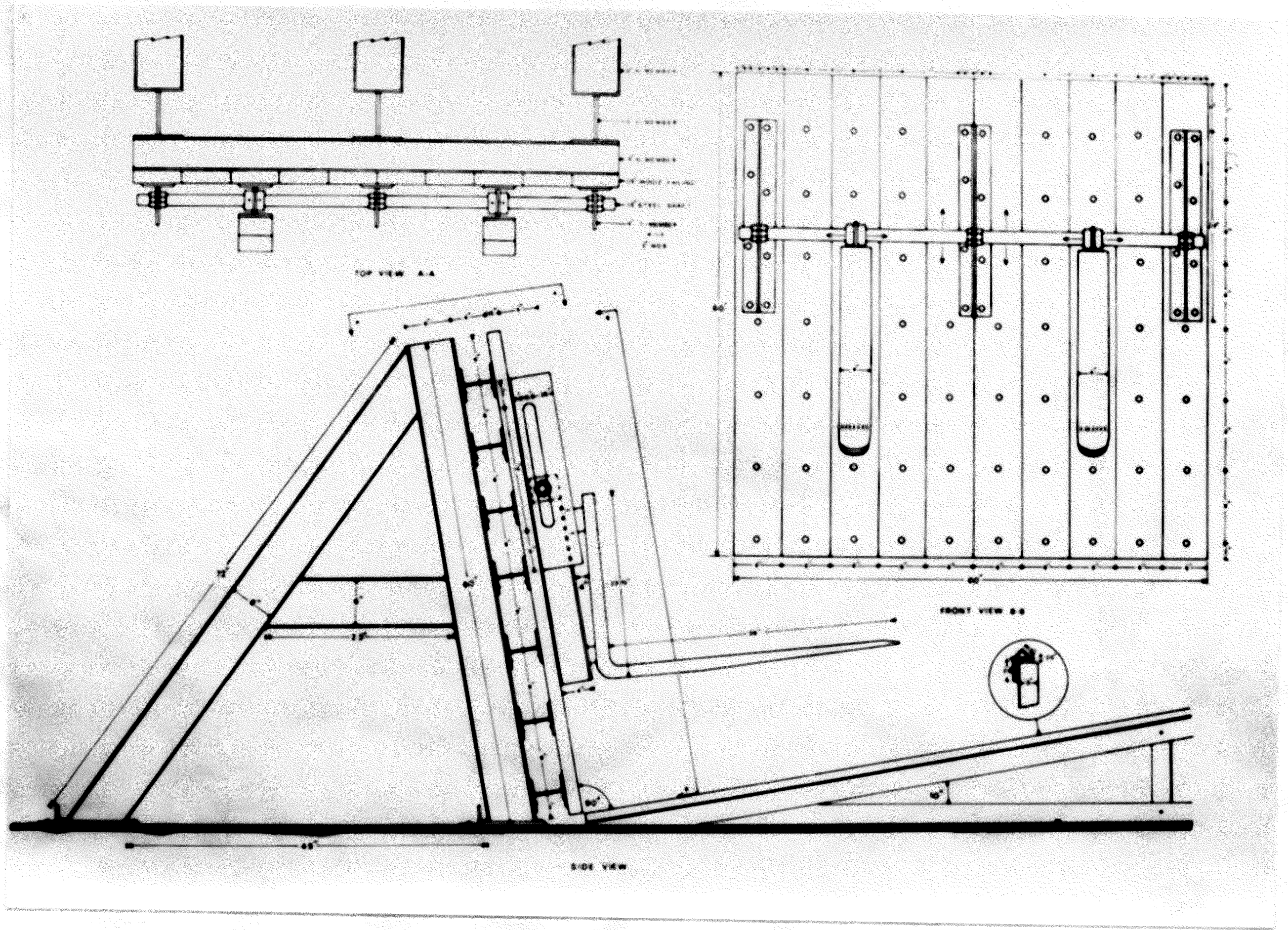
The described VPI&SU Conbur Impact Tester was constructed at the Wood Research and Wood Construction Laboratory of the College of Architecture of Virginia Polytechnic Institute and State University.

Appendix Figure V-1 shows side and front views of the stationary parts of the device. The standard track is inclined 10 degrees to the horizontal. The track gauge is $43\frac{1}{2}$ inches. The top-deck dolly dimensions are 60 x 48 inches.

The rigid backstop is affixed to the concrete floor serving as the base for the inclined track. The details of the design are shown in Appendix Figure VI-2. The forks affixed to the backstop are inclined downward 4 degrees to the direction of travel. The backstop (Appendix Figure VI-2) incorporates a hard-maple facing to which the forks are affixed in such a way that they can be moved laterally and vertically. Two standard I.T.D. $1\frac{1}{2}$ x 4-inch forged 3000-pound capacity forks bear upon the backstop. The

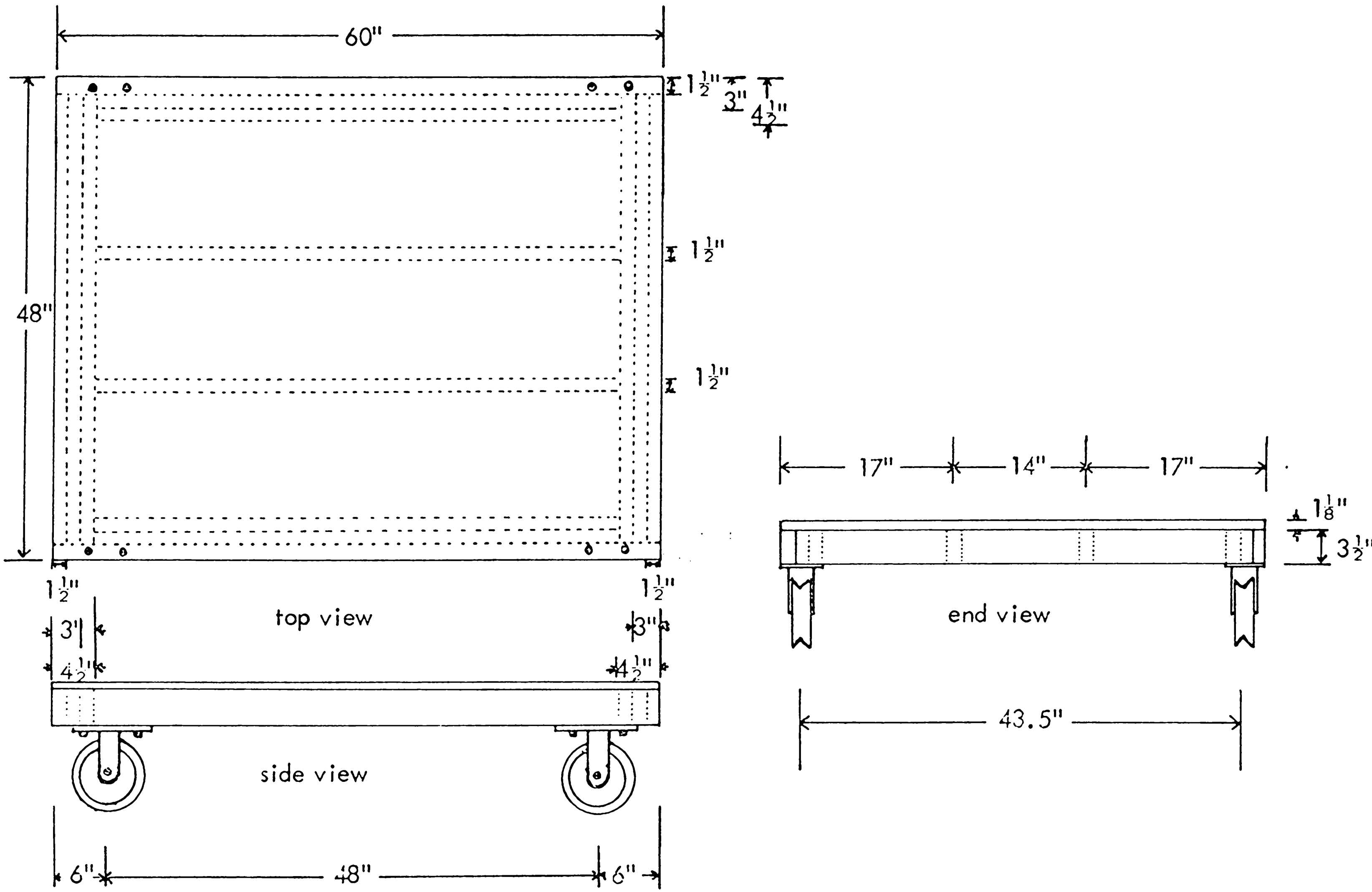


Appendix Figure VI-1. Side and plan view of VPI&SU Conbur Impact Tester.



Appendix Figure VI-2. Backstop details of VPI&SU Conbur Impact Tester.

fork arms are $21\frac{1}{4}$-inch high and have 36-inch tapered tines. At their heels, each contains a $\frac{3}{4}$-inch inner fillet which is the current industry standard. The dolly is shown in Appendix Figure VI-3.



Appendix Figure VI-3. Dolly details of VPI&SU Conbur Impact Tester.

APPENDIX VII

Detailed Specific Gravity and Leading-Edge Impact Resistance Test Data

Appendix Table VII-1

Number of Impacts Required to Damage Leading Edge

Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.	Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.
1[a]	27	.80	.82	25[a]	4	.61	.79
2[a]	25	.79		26[a]	8	.50	
3[a]	33	.84	.82	27[a]	5	.54	.83
4[a]	23	.84		28[a]	4	.72	
MEAN	27	.82	.82		5	.59	.81
5[b]	24	.79	.60	29	50	.52	.60
6[c]	5	.82		30	45	.57	
7	100	.82	.58	31	44	.66	.59
8[b]	25	.68		32[b]	12	.57	
MEAN	38	.78	.59		37	.58	.60
9	105	.84	.61	33	40	.70	.62
10	99	.81		34	43	.68	
11	57	.85	.60	35	45	.64	.58
12	112	.83		36	65	.75	
MEAN	93	.83	.60		48	.69	.59
13	13	.83	.47	37	15	.66	.48
14	15	.86		38	12	.76	
15	12	.84	.47	39[b]	5	.62	.43
16	12	.82		40[b]	4	.52	
MEAN	13	.84	.47		9	.64	.46
17	6	.79	.49	41	4	.71	.52
18	5	.81		42	5	.70	
19	4	.82	.50	43	5	.56	.54
20	4	.83		44	5	.55	
MEAN	5	.81	.50		5	.63	.53
21	3	.65	.46	45	5	.68	.46
22	5	.79		46	3	.57	
23	4	.82	.40	47	4	.68	.43
24	4	.83		48	4	.62	
MEAN	4	.77	.43		4	.64	.44

a: Stringer split during nailing.
b: Abrupt wood failure.
c: Leadboard splitting along pith.

Appendix Table VII-1 Continued

Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.	Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.
49[a]	5	.60	.83	73[a]	4	.46	.81
50[a]	3	.65		74[a]	4	.40	
51[a]	9	.57	.79	75[a]	4	.48	.78
52[a]	3	.60		76[a]	5	.47	
MEAN	5	.60	.81		6	.45	.86
53	10	.61	.56	77	11	.52	.58
54	17	.58		78	12	.50	
55	16	.56	.58	79	13	.46	.62
56	15	.64		80	9	.48	
MEAN	14	.60	.57		11	.49	.60
57[b]	5	.57	.60	81	6	.44	.59
58	12	.58		82	9	.47	
59	38	.54	.59	83	11	.45	.60
60	29	.56		84	13	.48	
MEAN	21	.56	.60		10	.46	.60
61	10	.62	.48	85	6	.47	.47
62[b]	4	.60		86	7	.46	
63[b]	3	.62	.48	87	8	.46	.50
64	8	.60		88	11	.54	
MEAN	6	.61	.49		8	.48	.48
65	3	.67	.55	89	4	.52	.50
66	3	.60		90	4	.49	
67	6	.61	.50	91	5	.49	.52
68	3	.60		92	5	.48	
MEAN	4	.62	.52		4	.50	.51
69	3	.55	.42	93	3	.42	.44
70[b]	2	.59		94	4	.55	
71	4	.53	.43	95	3	.46	.43
72	3	.55		96	3	.41	
MEAN	3	.56	.42		3	.46	.44

a: Stringer split during nailing.
b: Abrupt wood failure.

Appendix Table VII-1 Continued

Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.	Test-Pallet Number	Number of Impacts	Leadboard S.G.	Stringer S.G.
97[a]	6	.55	.81	121[a]	4	.44	.83
98[a]	10	.48		122[a]	6	.38	
99	36	.57	.83	123[a]	3	.38	.84
100	49	.59		124[a]	5	.54	
MEAN	25	.56	.82		4	.44	.84
101	12	.54	.56	125	12	.51	.58
102	11	.60		126	4	.40	
103	10	.56	.60	127	4	.45	.59
104	13	.54		128	3	.38	
MEAN	12	.56	.58		6	.44	.58
105	14	.50	.60	129	6	.39	.58
106	14	.52		130	14	.51	
107[b]	3	.51	.60	131	4	.43	.60
108	8	.48		132[d]	27	.45	
MEAN	10	.50	.60		13	.45	.59
109	10	.53	.48	133	5	.44	.42
110	6	.46		134	5	.44	
111	7	.54	.47	135	3	.41	.42
112	13	.49		136	7	.52	
MEAN	9	.51	.48		5	.45	.42
113	12	.57	.54	137	4	.46	.49
114	7	.58		138	4	.50	
115	4	.60	.49	139	3	.42	.55
116	9	.47		140	4	.43	
MEAN	8	.56	.52		4	.46	.52
117	3	.60	.43	141	2	.40	.38
118	4	.55		142	3	.42	
119	3	.52	.44	143	3	.42	.43
120	4	.50		144	3	.44	
MEAN	4	.54	.44		3	.42	.40

a: Stringer split during nailing.
b: Abrupt wood failure.
d: No lifting of leadboard from center stringer prior to leadboard splitting.

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THE EFFECT OF STRINGER DESIGN AND LEADING-EDGE DESIGN
ON THE STRENGTH CHARACTERISTICS
OF WOODEN PALLETS

by

James Richard Reeves

(ABSTRACT)

Impact shear and static flexure tests were performed on pallet stringers notched with six different fillet radii. These notches were cut with a band-saw or a stringer-notcher. Attempts were made to reduce the incidence of stringer fracture between the notches (a) by nail-reinforcing the stringers adjacent to the inner notch ends and (b) by retarding longitudinal moisture movement through the notch ends by notch coating. The leading-edge design of the pallet was studied by determining its impact resistance if fabricated with leadboards and stringers of different species and specific gravities.

The impact shear resistance and the flexural strength of notched pallet stringers increased with increasing notch fillet radii. The optimum fillet radius was one inch. No performance difference was found between the band-sawn and machine-shaped notches. Nail-reinforcing slightly increased the immediate flexural strength at initial failure of green stringers; did not increase the delayed flexural strength of seasoned stringers; and increased their immediate and delayed ultimate flexural strength. Notch-coating progressively increased the delayed ultimate flexural strength during the seasoning period.

Leadboard and stringer specific gravity effected the leading-edge impact resistance of wooden pallets. It increased more rapidly if the leadboard specific gravity was increased. An increase in the stringer specific gravity did not necessarily increase the leading-edge impact resistance. Optimum leading-edge impact resistance should be attained by using high-density lumber assembled with a supplementary nail driven through the leadboard into the center stringer, provided lumber splitting is avoided.