The Development of a Durability Procedure for Pallets with Structural Panel Decking

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(ABSTRACT)

The Pallet Design System (PDS) is a widely accepted engineering procedure for comparing the performance of competing pallet designs. As part of a new version of the PDS, the objective of this study was to develop a durability model for pallets with structural panel decking.

An accelerated rough material handling test system, "the VPI unit-load material handling FasTrack", was developed to simulate pallets used in the unit-load material handling environments. 100 pallets representing 14 different designs were tested in the "FasTrack". Damages to these pallets were recorded after each test cycle. A procedure relating damage to repair cost was developed. The effect of panel-deck pallet design on the resistance to damage was evaluated in terms of the total number of damaged parts and average damage cost or repair cost. Test results indicate that panel grade and type, species of related wood parts, size of stringer and deckboards, joints, and pallet configurations affect the resistance of panel deck pallet to damage.

The plots of average total damage cost, C_t, adjusted for repair as a function of test cycle, U, fit the equation: $C_t = a^U - 1$. The equation provided good fits to all the pallet

designs tested. Using the initial purchase prices, the average cost and the economic life were calculated for all the pallet designs.

The VPI "FasTrack" was calibrated based on the number of physical handlings and the amortized life. Three typical in-field handling environments were compared with the VPI "FasTrack". It concluded that the 30-cycle test period in the VPI "FasTrack" simulates between 2 to 5 years of field uses depending on the field handling system being simulated. Thirty Canadian Pallet Council (CPC) pallets with known 7 years of amortized life in the field were tested in the VPI "FasTrack". The 30-cycle test in the VPI system simulated 6 years of use in the similar handling environment of the CPC pallet used by the grocery industry in Canada.

The average total damage costs for different pallet designs were related to pallet structural characteristics using multivariate regression analysis. The shear resistance through the thickness of the top panel deck, bottom deck flexural strength, pallet flexural strength, fastener withdrawal resistance, and pallet configuration were used to predict the total damage cost. A multiple regression model was developed. The model was verified by comparing the predicted values with the tested values of 12 panel deck pallets representing 2 designs. The results indicated that the model is reliable for the future predictions.

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1.0 INTRODUCTION

1.1 Problem Statement

The wooden pallet represents one of the most economical systems for unit-load material handling. The number of pallets produced in the U.S. has increased from 57 million pallets in 1959 to over 500 million by the early 1990's (NWPCA, 1991). The pallet industry is the second largest consumer of lumber produced in the U.S. Pallets constructed with structural panel deck or decks, especially APA rated sheathing plywood, are an alternative to lumber deck pallets. America Plywood Association (APA) estimates the annual U.S. usage of structural panels in material handling devices at 1,015 million square ft (3/8" basis) (White and Loferski, 1987). Since wooden pallets are the most dominant unit-load platforms used in material handling, it is not surprising that an approximated 10 to 15 million panel-deck pallets would be fabricated and used annually in the U.S. (White and Loferski, 1987).

A comparative study of lumber and plywood decked pallets indicates that plywood-deck pallets have longer life spans and lower cost-per-use than lumber-deck pallets. The study also states that pallets with softwood plywood decks are 45 percent more durable than comparable lumber deck pallets assembled with stiff-stock nails (White and Wallin, 1988). Another advantage of structural panel pallets is that their smooth deck or decks reduce the risk of damage to the product being shipped. This is an important feature since the cost of damaged goods can far exceed pallet repair or replacement costs (APA, 1982).

The Pallet Design System (PDS), which is a reliability-based structural design procedure, is a widely accepted engineering procedure for comparing the performance of competing pallet designs (Loferski and McLain, 1987). The PDS enables the user of pallets to select the most efficient design for a specified service environment. The PDS contains three design procedures which predict the static strength and stiffness, lateral collapse resistance, and durability of wood pallets. However, the current versions of PDS cannot predict the performance of pallets constructed with structural panel deck or decks.

The study reported here is part of the overall research effort at Virginia Polytechnic Institute & State University, sponsored by the American Plywood Association (APA) and the National Wooden Pallet and Container Association (NWPCA), aimed at the development of a new version of PDS for panel-deck pallets. Integral to this research effort is the development of a durability model.

The durability of a wood pallet is defined as its economic life (Wallin, 1984). The economic life is the number of uses at which the average cost per use is a minimum (ASME, 1988). The existing PDS durability model for lumber deck pallets is a semi-empirical procedure which predicts the durability of a pallet based on its structural design, the characteristics of material handling environment, and the purchase price of the pallet.

The cost-per-use is the total cost divided by the number of uses. The total cost to use the pallet is comprised of the initial purchase price plus the total damage cost.

The cost-per-use is defined by Wallin in Equation 1.1.

$$C_a = \frac{(P + C_t)}{U} \qquad [1.1]$$

Where:

C_a = cost-per-use
P = initial purchase price
U = the number of uses
C_t = total damage cost after the number of uses, U

According to Equation 1.1, the average cost per use can be determined if the total damage cost is known after each use. One can determine the economic life by differentiating Equation 1.1 as shown in Equation 1.2.

$$\frac{d[\frac{P + f(U)}{U}]}{d(U)} = 0 \qquad [1.2]$$

Where:

f(U) = total damage cost as the function of U.
P = initial purchase price
U = the number of use

It should be noted that Equation 1.2 has to have an unique solution. That is a minimum of cost-per-use occurs during the pallet's life. The model of a pallet durability proposed by Wallin (1984) is a theoretical model. However, the determination of f(U) in the model is empirical and based on the pallet damages recorded during the PEP study

(Wallin and Whitenack, 1984).

The total damage cost of a pallet is calculated as the sum of the costs of repairing all the damaged components. Hence, the number of damaged components and their related repair costs are needed to determine the total damage cost. Damage data for lumber deck pallets are available from an extensive in-field test program known as Pallet Exchange Program (PEP). As have been extensively evaluated in Appendix A, the damage data from the PEP study cannot be used to model pallet durability even though such model is being used in the Pallet Design System (PDS). Furthermore, there were very few panel deck and block pallets tested in the PEP study (Wallin, 1984).

In order to extend the durability predictions of PDS for panel deck pallet, a test program specifically designed for such purpose was conducted.

1.2 Research Objectives

1. Determine the relationship between the total damage cost and number of uses for pallets containing structural panel decking
2. Determine the relationship between panel deck pallet structural design and the resistance to damage.
3. Develop an empirical model of a pallet which relates the structural design to durability of pallets with structural panel decking.

This research also included a detailed study of the existing procedure for predicting the durability of lumber deck pallets developed by Wallin (1984).

2.0 LITERATURE REVIEW

2.1 General Description of Pallet Structural Design

2.1.1 Pallet Classifications

Pallets are generally described by class, type, and style (NWPCA, 1992). Stringer and block pallets are the two basic pallet classes. Based on the openings accepting handling equipment in pallet ends, pallets are defined as three types: 2-way entry, partial 4-way entry, and full 4-way entry. Unnotched stringer pallets are typical 2-way pallets. Notched stringer pallets and block pallets with overlapping bottom stringerboards and deckboards are partial 4-way pallets. Block pallets with perimeter, unidirectional or no bottom decks are full 4-way pallets. The style denotes the features of the top and bottom decks, such as single-face, flush, non-reversible pallet, double-face, flush, reversible pallet, etc.. According to McCurdy and Phelps (1992), the most widely produced pallet style in the U.S. is the flush stringer, double-face, non-reversible pallet, and one third of pallets produced are 48" X 40".

2.1.2 Panel-Deck Pallets

Panel-deck pallets are those pallets having at least one structural panel deck, such as plywood and OSB. The classes, types, and styles of panel-deck pallets are defined as they are for lumber deck pallets. However, panel-deck, block pallets are usually fabricated with the panel directly fastened to the blocks while the lumber-deck, block pallets are fabricated by using stringer boards between the deckboards and blocks. It is worth noting that the majority of structural panels used in panel-deck pallets are structural plywood. The plywood pallet standard, PP 61-90 (APA and NWPCA, 1990) specifies two-way, partial four-way, and four-way plywood pallet designs. The plywood specified in this standard conform to the U.S. Product Standard PS 1-83 for Construction and Industrial Plywood or PRP-108, APA Performance Standard and Policies for Structural-Use Panels. The configurations of commonly used panel-deck pallets are summarized in Table 2.1.

As material handling becomes more automated higher quality pallets are increasingly used for efficient handling. Pennington (1972) and White (1987) report that plywood-deck pallets provided the most economical pallet with a great many assets not found in lumber-deck pallets. A plywood pallet provides a smooth deck which will not damage merchandise, which has high impact and concentrated-load resistance, is dimensionally stable, minimizes the extent of nail pop, and which will remain square when hit by a lift truck or dropped on one corner. Lyons (1970) also reports that a plywood pallet provided more years of service than a conventional lumber pallet, thus costs less to use.

Table 2.1 -- The configurations of commonly used panel-deck pallets

Pallet classes	Pallet Type	Top deck	Bottom deck
Stringer pallet	2-Way	Panel[1]	Lumber deckboards
		Panel[1]	Panel deck
	Partial 4-Way	Panel[1]	Lumber deckboard
Block pallet	Full 4-Way	Panel	Panel base[2]
		Panel	Unidirectional base[3]
		Panel	Perimeter base

Note:

1 -- leading deckboards are commonly used with panel deck in stringer pallets

2 -- panel bottom deck with 4 wheel openings are often used in full 4-way block pallets

3 -- bottom deckboards are either parallel or perpendicular to the pallet length

2.1.3 Current Design Procedures for Plywood Pallets

The design of panel-deck pallets, especially plywood pallets, is based on the contents of the Specifications for Softwood Plywood Pallets, PP61-90 (APA, 1990), Plywood Design Manual -- Pallets (APA, 1975), and the APA Industrial Use Guide -- Materials Handling (APA, 1990). All these guides are jointly documented by National Wooden Pallet and Container Association (NWPCA) and American Plywood Association (APA), and based on extensive research programs conducted by USDA Forest Service, Forest Product Laboratory (FPL), APA, and NWPCA. These design procedures specify the commonly used configurations and materials selections such as plywood, lumber, and various fasteners for custom and industrial grade plywood pallets. Moreover, the proper plywood deck (or decks) can be determined using the load/span tables with additional consideration for such variables as repeated exposure to weather. A more generalized design procedure was developed by Elias (1986). This procedure can aid a designer relate certain plywood deck pallet design for a limited configuration of load supporting conditions. However, this procedure will not aid the designer in predicting the durability of such pallet design.

2.2 General Description of Structural Panels

Structural panel is commonly used to refer collectively to those load bearing panels, such as structural plywood, waferboard, oriented strand board (OSB), etc. Some of the major structural uses for these panel are: 1) roof, floor, and wall sheathing; 2) stressed-skin panels, I-beams, and sandwich panels; and 3) pallets and bins. Structural panels are usually manufactured in the size of 4 ft X 8 ft, and they are available in a number of standard thicknesses ranging from 1/4" to 1-1/8" although other sizes are also manufactured. During 1985, Structural plywood constitutes approximately 85 percent of total structural panel productions in the United States (Breyer, 1990).

2.2.1 Structural Plywood

Plywood panel is made up of a number of veneers. The veneers are cross-laminated and glued into a plywood panel with an odd number of layers. It is the cross-laminating that provides plywood with its unique strength characteristics. This cross lamination provides dimensional stability and reduces cracking and splitting. The direction of wood grain in the face veneer of the plywood panel significantly influences panel strength and stiffness. The strength properties parallel to face grain direction are higher than that in perpendicular to face grain direction. In the pallet construction, the face grain of plywood panel is often parallel to the 48" direction of 48" x 40" pallets to achieve a higher strength over longer pallet span. In fact, the length of panel deck, block pallets is defined by the direction of face grain of the plywood or strand direction of

OSB.

A large number of species of wood are allowed to be used to manufacture plywood. The species used in plywood construction are classified into 5 groups according to strength and stiffness. Group 1 are the strongest and group 5 the weakest. The species group of the face and back veneers determine the allowable stresses of plywood, and the section properties of plywood are determined based on the species of group 4 in the inner layers (Breyer, 1990).

2.2.2 Other Structural Panels

In addition to plywood, structural panels also include composite panels, waferboard, oriented strand board (OSB), and structural particleboard. These structural panels are not veneer based. They involved some form of reconstituted wood products. Waferboard is a nonveneer panel manufactured from reconstituted wood wafers. These wafer-like wood particles or flakes are compressed and bonded with phenolic resin. The wafer may vary in size and thickness, and the direction of the grain in the flakes may be randomly or directionally oriented. The wafer may also be arranged in layers according to size and thickness.

Oriented strand board (OSB) is a nonveneer panel manufactured from reconstituted wood strands. The strand-like wood particles are compressed and bonded with phenolic resin. The wood strands are directionally oriented. The wood fibers are arranged in perpendicular layers (usually three to five), and thus cross-laminated in much the same manner as plywood. Unlike structural plywood, no species group is specified to these nonveneer panels.

2.2.3 Grades and Specifications of Structural Panels

For many years the specifications covering the manufacture of plywood were prescriptive in nature. This means that a method of constructing a plywood was fully described by the specification. For each grade of plywood, the species group, veneer grades, and other important factors were specified.

U.S. Product Standard PS 1-83 for Construction and Industrial Plywood contains the manufacturing of all veneer panels (U.S. Department of Commence, 1983). For many years, this product standard was a prescriptive only specification. Although PS 1-83 still contains prescriptive requirements, it now also contains requirements for plywood based on performance.

The concept of a performance standard has been adapted to the manufacturing of structural panels because a prescriptive type of specification did not lend itself to the development of some of the newer panel products. These panels can be manufactured in a number of different ways using a variety of raw materials. The PRP-108, APA Performance Standard and Policies for Structural-Use Panels (APA, 1990) exclusively deals with how a product must perform in a designated application rather than from what or how the product must be manufactured. The performance rating has resulted in the development of new performance rated panels including veneer and nonveneer-based structural panels. Structural panels are specified according to their end use. For building applications, panel grades include Rated Sheathing and Sturd-I-Floor grades. Sheathing grades are normally used for roof, floor, and wall sheathing.

In the trade, Performance Rated plywood is also called by C-C or C-D plywood based on the grades of face and back veneers. C-C plywood is generally exterior-type plywood, and C-D is generally available with exterior glue, which is equivalent to APA Rated Sheathing, Exposure 1 (APA, 1990). Where added strength is required, these grades can be upgraded to Structural 1 Rated Sheathing. The Structural 1 Sheathing grades permit the group 1 species only. Sheathing grades include panel thickness and span rating. The span rating on a sheathing panel is a set of two numbers. The number on the left in the span rating is the maximum recommended span in inches when the panel is used as roof sheathing. The second number is the maximum recommended span in inches when it is used as subflooring. Thus, the same span rating may be found on a thin panel that is fabricated from a strong species of wood and a thicker panel that is manufactured from a weaker species. Panels can be manufactured with different thickness for a given span rating.

A typical grade-mark for nonveneer performance rated panels, such as OSB, includes a number of the same items found in a plywood sheathing stamp. However, the grade-mark found on these panels does not contain reference to PS 1-83, and also does not have veneer grades (e.g., C-D) shown in the stamp. Moreover, the Structural 1 Rated Sheathing is not applicable to these nonveneer based panels because on species group is specified in these panels.

The design values of the structural panels used for roof, floor, and wall sheathing are published by APA, Pittsburgh Testing Lab, and Teco Products and Testing Corporation (TECO). The allowable design stresses and section properties for APA performance rated structural-use panels are tabulated in the Design Properties of APA Performance Rated Structural-Use Panels, N370A (APA, 1991).

All structural panel can be used in the manufacture of pallets. However, in this study only APA performance rated plywood and OSB will be used. The results should be applicable to panels marked by other agencies since allowable stresses and section properties are the same.

2.3 The Performance of Pallets with Structural Panel Deck

2.3.1 Survey of Plywood Deck Pallets

In order to better understand the uses of plywood pallets and promote the use of structural panels in pallets, Pennington and Carney (1972) surveyed uses of plywood pallets. The results of this survey are summarized below.

Type of pallets being used: 255 firms using 1,040,019 plywood pallets were surveyed. 62 percent of plywood pallets were warehouse and 74 percent of these warehouse pallets were 3 stringers and 9 blocks designs. 75 percent of the plywood pallets had bottom decks. Fifty percent of them were plywood and the other 50 percent contained lumber bottom decks. 70 percent of the pallets used threaded nails fastening decks to stringers or blocks. The dominant pallet size was 48" x 40". Table 2.2 shows the summary of type of plywood pallets used in the pallets surveyed.

Type of plywood being used: 90 percent of plywood in the pallets were standard sheathing grades. 3/4" and 5/8" thicknesses accounted about 80 percent. The survey did not specify the grades and/or span ratings.

Handling condition of these pallets: The average load carried by these pallets was 2,000 lbs to 3,000 lbs. The maximum stacked load was 6,096 lbs per pallet. Most of these plywood pallets were used in warehouse and handled by forklift, pallet jack, roller conveyor, and palletizers. The handling of these pallets varied from 100 to 900 times per year with an average of 200 times. According to the author, 37 percent of the pallets were exposed to rough or very rough handling situations.

Table 2.2 -- The usage of 1,014,019 plywood deck pallets surveyed by Pennington and Carney (1972)

Attributes	Percentage [1]
Dimension of Pallets	45% (48" X 40")
Stringer Pallets	35% (3 stringers)
Blocks Pallets	30% (4" X 6" block)
Double Deck Pallets	75% (Double decks)
With Plywood Bottom Deck [2]	50% (Panel deck)
With Lumber Bottom Deck [2]	50% (Lumber deck)
Fastener used	70% (Threaded Nails)
Products Carried	60% (Bagged & Cartoned)
Handling	90% (Forklift, Hand jack)

Note:

1 -- percentage of total 1,040,019 of plywood surveyed
2 -- bottom deck for both stringer and block pallets

Actual life expectancy of plywood pallets: The damage to plywood in the pallets was mostly the splintering of edges. The damage to stringers and blocks constituted 22% and 11% of the total damage, respectively. The average life expectancy for plywood pallets are 7 years comparing with 4 years for comparable lumber deck pallets. The average purchase price of plywood and lumber pallets at that time was $6.66 and $4.46, respectively. About 75 percent of plywood pallet users claimed that no repair were performed, while more than 50 percent of lumber pallets users spent more than $1,000 of repair. The author predicted that plywood pallets users can enjoy about a 20 percent savings in annual cost per pallet when compared with lumber deck pallets. No attempt was made to correlate different plywood pallet design with structural durability.

The survey also indicated that the loads, number of handlings, pallets size, and even life expectancy varied between different pallet users.

2.3.2 Field Testing of Plywood Deck Pallets.

An extensive test of plywood pallets was conducted by APA in 1967, which includes an in-service test, a laboratory test, and a national survey. The purpose of this study was to verify the serviceability and value of plywood pallets. The in-service test was conducted in two material handling systems during the period of time from 1962 to 1970 (Lyons, 1970). The purpose of the in-service test program was to evaluate the actual performance of plywood pallets and determine the relationship between pallet design and performance. The study concluded that plywood deck pallets provided excellent service in food manufacturing and distribution, but plywood bottom-deck boards did not perform well when the pallets were stacked on bagged goods. Different fasteners and nail patterns were also investigated. It was found that nails with large diameters exhibited less popping, and more nails placed at stringer ends provided less susceptibility to joint failure. The results of this test were the basis for the specification of plywood pallets. No attempts were made to compare the effects of different grades of structural panels on the performance of the different plywood pallet designs. Also the performance criteria was not clear. The life expectancy and cost-per-use of plywood pallets were not investigated.

In addition to the above in-service test, 5 types of plywood pallets were studied during the PEP study (Wallin and Strobel, 1973). Compared lumber deck pallets containing the same wood species and deck member thickness, Plywood pallets with 5/8" decking were 45 percent more resistance to damage. In terms of resistance to first damage, the thickness of the plywood and number of veneers had no significant effect on pallet durability (White, et al 1987). The analysis of these test results is discussed in detail in Appendix A.

In service tests of panel deck pallets are limited and the results reveal little regarding the relationships between design and performance.

2.3.3 Laboratory Testing of Panel Deck Pallets

Many attempts have been made to relate pallet performance in laboratory tests to performance in service (Stern, 1968, 1969, 1976; Stern, 1972; Kertenacker, 1973, Osborn, 1985). Therefore, it is not surprising that many laboratory tests for plywood deck pallets have been conducted. Recently, the Pallet and Container Laboratory at VPI & SU conducted a series of comparative tests of plywood-deck block pallets and lumber-deck pallets. The strength and stiffness racked across stringer (RAS) and racked across deckboard (RAD), and inclined edge impact resistance of block type plywood pallets were evaluated in the laboratory (White, 1989, 1990). Plywood pallets were usually stronger and less stiff than lumber deck pallets. The face veneer grain orientation can balance the structural strength in different directions. From the test data, it seemed that the grade of plywood affects the pallet strength and stiffness, but did not affect the incline impact test (White, 1989). The study also shows that typical failure modes of plywood decks to be localized edge compression damage. Lumber pallets fail in the form of joint separation and board splitting. No joint separation was exhibited in plywood pallets. This may indicate fasteners affect less the durability of plywood deck pallets. The grades of plywood were also compared (White, 1990). According to the test results, C-C grade plywood was better than C-D grade plywood in terms of strength, stiffness, and incline edge impact test. This implies that the grade of structural panels may affect the durability of panel deck pallets although some contradictions were found in the results of these laboratory tests.

In order to be able to better predict the durability of plywood deck, block class pallets, a rough handling test program simulating actual use of the pallets was conducted by Proctor & Gamble Corporation (P&G) (Cauffield and Fogler, 1989). This test program included handling devices and operations found in the real material handling system. Each cycle of the tests included 12 handlings which simulated an actual cycle through a distribution system. The handling devices included fork lift, pallet jack, trailer, storage racks, and palletizers. The VPI-unit load material handling "FASTRACK" used in this study is a modification of the P&G accelerated pallet test protocol. This will be discussed later in the section of test procedures.

30 plywood deck, block pallets were tested using 30 handling cycles, which simulated about 5 years of use in the dry grocery sector in the USA. Each pallet was inspected at the end of each cycle and damage was recorded. A statistical technique of survival testing was used to project the expected pallet life, and hence, annual repair costs. The test results indicated the plywood pallet had an expected average time to deck replacement of 8.7 years. This lead to the expectation that 11.5% of the pallets would need deck replacement each year. 5% would need block replacement, and 21% would need block renailing. The estimated total cost of these repairs was $1.12 per pallet per year. In this report, different damage criteria for repair or replacement were compared. The different criteria resulted in a different durability estimates and cost per use. This indicated that any comparison of pallet durability among pallets should be based on the same repair criteria.

2.4 The Pallet Design System PDS Model of Pallet Durability

In 1980 National Wooden Pallet and Container Association (NWPCA), the USDA Forest Service, and Virginia Polytechnic Institute and State University (VPI&SU) cooperatively developed a structural design procedure for stringer class, lumber deck pallets. The first generation, reliability-based structural design procedure known as the Pallet Design System (PDS) was completed in 1980. Based on user-specified information, PDS will generate estimates of the static strength, stiffness, and durability of the pallet. PDS analyses of pallets is part of the purchasing strategy of many fortune 500 corporations (White and Loferski, 1987). The design procedure is gaining widespread acceptance among those using wood pallets and its accuracy and reliability have been proven continually since it was in service in 1984 (White and Loferski, 1987).

The durability procedure in the current version of the PDS was developed by Dr. Walter B. Wallin of the USDA Forest Service based on the observations of pallet performance data during the in-service study known as "Pallet Exchange Program" (PEP)(Wallin et al, 1972).

2.4.1 The PEP Study

The increased use of pallets as shipping bases resulted in the increased exchange and interchange of pallets. This occurred within multi-plant facilities and within groups of firms that formed voluntary pallet pools. However, many such programs failed because no efficient method for comparing pallet performance between pallet designs existed.

The most comprehensive attempt to document and describe pallet performance as a function of design characteristics was initiated in 1968. The objectives of this program were: 1) to evaluate the performance of different pallet designs and, 2) to develop methods and procedures for establishing a National Pallet Exchange Program (PEP) in the United States (Wallin et al, 1972). Equal pallets were defined as pallets that would perform equally for the same cost. A detailed study of the performance of over 1,900 pallets under in-service conditions was conducted. These pallet designs included different species, such as hardwood lumber, softwood lumber, and plywood, and different fasteners, different structural designs, and different component sizes.

The 1,918 pallets were studied in 16 different material handling environments of the food industry, the alcohol beverage industry, the glass container industry, and the U.S postal service. They were used in commercial rail and truck shipping operations. Special efforts were made to insure that different pallet types received equal exposure to different handling environments. This study lasted 3 years from October 1967 to June 1971.

An analysis of the damage data from the study made possible the direct comparison of the performance of the different pallet designs. A comparison of particular component parts and the effects various design features had on the performance of those component parts was accomplished by describing damage in terms of damage frequency and damage severity.

During the PEP study, all the pertinent information was recorded using six separated data recording cards. For each pallet, these data cards contained the following information:

1) Quality characteristics of each part.
2) Description of each damage, such as number, location, and level to each pallet.
3) Part repair and replacement.
4) Total number of handling.

2.4.2 Durability of Pallets

To assemble the findings of the PEP study and other pallet research projects into a usable form, a semi-empirical model was developed for predicting the economic life. The durability model is a composite of several factors which were intended to reflect the impact of design characteristics on pallet durability.

The following discussion was based on information from Wallin and Whitenack (1984). Like many structures, a pallet has a certain useful life which is dependent on the conditions of use. The durability of a pallet is defined as the number of uses at which the average cost of use of the pallet is the minimum. The use of the pallet beyond this point results in a marginal cost of use greater than the average cost of use. At this point, it is less costly to replace the pallet than to continue to repair it. The durability of a pallet is expressed as years of service or number of handlings or trips and cost-per-use.

The durability of a pallet can also be expressed as physical life (ASME, 1988). The physical life of a pallet is the number of uses that can be obtained before the pallet is damaged sufficiently to make it unusable. At this point, it may be repaired at a cost to extend its life or replaced by a new pallet.

Number of uses A pallet use or trip constitutes a series of handlings. A handling is a single physical movement, e.g., picking up and setting down of a pallet, either empty or loaded. According to Wallin (1984), each time a pallet is moved from one plant to another plant, it is handled an average five times. Each such move of an empty or loaded pallet is called a trip. Thus, 50 handling represents about 10 trips. According to Wallin and Strobel (1976), one year of pallet use consists of an average 20 trips. That is that 100 handling represents one year of pallet use. The number of handling is a better measure of pallet life than the trip because it can be modified to suit many different handling conditions.

Damage Frequency In the current model, durability is related to the damage frequency. The damage frequency of a pallet is defined as the number of times that a pallet sustains damage during its useful life (Wallin, 1984). The patterns of damage for different pallet designs are different. The frequency of damage is different for different components in the pallet. Therefore, when comparing the performance of different pallet structures, the components damaged are identified, such as edge deckboards, center deckboards, edge stringers, etc. The frequency of damage to different components in different pallet design is summarized and shown in Table 2.3 for the PEP study. This data makes it possible to evaluate the effect of pallet design on the damage frequency. The following effects of pallet design characteristics on the damage frequency can be evaluated by simple comparisons.

(1) The effect of wood species on the damage frequency: The average damage frequency of pallets built with hardwood species (type 20, 1, 2, 3, 18, 28, 48, 4, and 5) was about 50 percent higher than that of pallets built with softwood species (type 13, 26, 16, 15, 21, 11, 9, 10, and 12).

(2) The effect of butted boards on the damage frequency: The butted board hardwood pallets (type 18, 28, and 48) were about 20 percent less in damage frequency compared with spaced deckboards hardwood pallets (type 2 and 1). The effect of butted boards was more significant in softwood pallets. The damage frequency of spaced deckboard softwood pallets (type 13, 26, 16, and 14) were about 90 percent higher than the pallets with butted deckboards (type 15).

(3) The effect of moisture content on the damage frequency: The damage frequency of pallets with green deckboards (Type 3) was about 60 percent higher than that of pallets with air dry deckboards (type 2 and 1).

(4) The effect of plywood deck on the damage frequency: The average damage frequency of softwood lumber deck pallets (Type 13, 26, 16, 14) was about 80 percent higher than that of softwood plywood pallets (Type 9, 10, 11, 12, and

Table 2.3 -- The frequency of damage to different components of the pallets used in the PEP study [1]

Pallet Type[2]	Deckboard		Stringer		Pallet
	End[4]	Center	Edge	Center	
20	0.91	0.60	0.28	0.03	1.82
1	1.59	1.03	0.27	0.03	2.92
2	0.96	0.57	0.47	0.04	2.04
3	2.04	1.74	0.57	0.11	4.06
18	0.63	0.85	0.10	0.02	1.60
28	0.88	0.31	0.31	0.04	1.54
48	0.36	0.28	0.36	0.00	1.00
4	1.70	1.56	0.70	0.24	4.20
5	2.01	1.38	0.65	0.15	4.19
13	2.75	1.54	0.67	0.20	5.16
26	3.23	1.35	0.75	0.10	5.43
16	1.80	0.91	0.69	0.07	3.17
14	2.38	1.58	0.15	0.05	4.16
15	0.82	0.38	0.46	0.10	1.77
21[3]	1.33	0.71	0.45	0.14	2.63
11[3]	1.11	0.51	0.76	0.22	2.60
9[3]	2.29	0.67	0.47	0.08	3.51
10[3]	1.40	0.37	0.19	0.07	2.03
12[3]	1.04	0.35	0.35	0.06	1.80
17	0.63	0.13	0.13	0.00	0.89
22	0.67	0.08	0.00	0.00	0.75

Note:

1 -- damage frequency is calculated as the number of damages divided by the number of pallets tested

2 -- PEP ID is used refers to Wallin (1976, 1984)

3 -- plywood pallets

4 -- leading deckboards including both top and bottom decks

21).

(5) The effect of plywood thickness on the damage frequency: The damage frequency of 1/2" plywood pallet (type 9) was about 35 percent higher than that of 5/8" plywood pallet (type 11).

(6) The effect of fastener on the damage frequency: Both the type of nail and the number of nails per joint affect the damage frequency. The damage frequency of the pallet with stiff-stock nails (type 2) was about 12 percent higher than that of pallets with hardened steel nails (Type 20). The damage frequency of pallets with 3 nails per joint at end deckboards (type 18) was about 5 percent higher than that of pallets with 4 nails per joint at end deckboards (type 28).

More detailed studies of the effect of the characteristics of the PEP pallets on the damage frequency by pallet parts are referred to Wallin and Strobel (1976). Based on these comparisons, it is not surprising that the type 26 pallet design had the highest damage frequency among all the PEP pallet designs. The type 26 pallet was built with the following characteristics: a) green softwood species rather than dry and/or hardwood species; b) stiff stock nails rather hardened steal nails; c) 3 nails per joint instead of 4 nails per joint; d) spaced deckboard construction instead of butted deckboards.

The damage frequency of a pallet was calculated as the total number of damages divided by the total number of pallets tested. According to Wallin and Whitenack (1984), the damage frequency, F, accumulates in a manner similar to compound interest. Therefore, F is a function of the number of trips, U, as shown in Equation 2.1

$$F = (1 + R)^U - 1 \qquad [2.1]$$

Where:
R = the damage rate
U = the number of trips
F = the number of damages at the given level of use, U.

According to Wallin, the damage rate, R, is constant related only to the pallet structural design and the condition of use. There is no verification of Equation 2.1 in the literature. An evaluation of the reliability of this equation is in Appendix A.

Damage Severity In addition to measuring the frequency of damage, the severity of each damage was also measured because it was related to the cost of repair. During the PEP study, a descriptive scale of severity was developed. The detailed description of this damage severity scale is in Appendix B. Minor damage does not influence the structural strength of the pallet; moderate damage causes a weakening of the structure, but does not require a repair; severe damage causes a major weakening of the structure, and inactivates the pallet until it is repaired. If a part was damaged more than once at different points in time, the second damage was recorded with a severity code representing the composite damage of all damages to that part.

In order to assess the relative severity of damage for different species of wood, different pallet structures, and different part locations, the severity code numbers assigned to each damage incident was summed for each part number. These sums were then aggregated to a total severity for the pertinent category of the pallet design characteristics. The total severity was then divided by the total number of damaged parts for the pertinent category. When the severity was divided by the number of damaged parts, it provided a measure of the extent of the damage. The damage severity for the PEP pallet designs is discussed in detail in Appendix A.

These measures of severity were employed together with the frequency of damage to assign monetary cost to the damage of a pallet.

Cost of Damage In order to equate all types of damage, all frequencies, and all severity, the severity codes were translated into cost values derived from empirical data. The costs to repair the pallets were accumulated for the pallets used in the PEP study, and from repair records of various industrial users. This analysis resulted in a regression equation relating cost as a dependent factor of the severity of the damage. The regression was of the form, $\log Y = a + bX$, where Y is the cost of damage and X is the severity of damage as measured by the severity code numbers. The regression coefficients result from regressing those damages included in the moderate and severe classes. The regression was extrapolated in such to estimate the cost of minor damages. The cost values applied to the severity codes are in Table 2.4.

From the regression formula and recorded damage severity code numbers, all the costs of each pallet used in PEP study were calculated. The damage cost for each pallet is shown in Table 2.5.

Table 2.4 -- Current damage costs for each damage severity code for the PEP study

Severity Class	Severity Code [1]	Damage Cost ($)
Minor	1	0.059
	2	0.089
	3	0.133
Moderate	4	0.200
	5	0.300
	6	0.450
Severe	7	0.675
	8	1.013
	9	1.519

Note:

1 -- a detailed physical description for each damage severity level is found in Appendix B
2 -- damages with these levels require repair

Table 2.5 -- The total damage costs to the pallets studied by Wallin and others during the PEP study

Pallet Type[1]	Number of trips	Costs per damage ($)[2]	Number of damages [3]	Total damage costs ($)[4]
20	53	0.227	1.82	0.413
1	49	0.165	2.92	0.482
2	40	0.342	2.04	0.698
3	42	0.265	4.06	1.076
18	44	0.244	1.60	0.39
28	46	0.185	1.54	0.285
48	49	0.181	1.00	0.181
4	54	0.382	4.20	1.604
5	44	0.360	4.19	1.508
13	46	0.301	5.16	1.553
26	48	0.255	5.43	1.385
16	48	0.270	3.17	0.856
14	47	0.161	4.16	0.670
15	39	0.160	1.77	0.283
21	51	0.347	2.63	0.913
11	48	0.271	2.60	0.705
9	54	0.286	3.51	1.004
10	49	0.249	2.03	0.505
12	49	0.225	1.80	0.405
17	15	0.334	0.89	0.297
22	42	0.249	0.75	0.187

Note:

1 -- PEP ID used by Wallin (1976, 1984)
2 -- the cost per damage based on average damage severity
3 -- the damage frequency per pallet
4 -- the total damage costs is the product of average damage cost and the damage frequency

The Economic Life of a Pallet Design The durability of a pallet was defined as economical life. That was the number of trips at which the cost-per-use of the pallets was the minimum. The cost-per-use (A) was calculated as follows:

$$A = \frac{T}{U} \qquad [2.2]$$

Where:
T = total cost of pallet uses
U = number of trips (4 to 6 handling per trip)

The total cost, T, was related to the purchase price, damage frequency, F, and severity, S, of a pallet after the number of uses, U. Given the accumulated damage severity of a type of pallet, the average damage cost, C_d, based on the average severity of the damages was calculated in Equation 2.3 which was the result of a regression analysis of actual repair costs and observed damage severity.

$$C_d = c\, b^S \qquad [2.3]$$

Where:

S	=	the damage severity of a pallet
b	=	a design constant = 1.5 for lumber deck pallets
c	=	economic coefficient
C_d	=	the average damage cost

Actually, b and c were least fit regression coefficients. Since the repair costs for the same severity of damage changes with advance in repair technology, inflation etc., these coefficients are periodically adjusted. Wallin (1984) proposed the following variables for adjusting c: (a) average earnings; (b) consumer price index; (c) consumer service index; and (d) produced materials index. All the above variables can be obtained from "Economic Indicators", Council of Economic Advisors, U.S. Government Printing Office. For details of this adjustment of coefficient, c, see Wallin (1984).

The average damage cost of a pallet was assumed dependent on the number of uses or trips. The evaluation of this assumption is discussed in detail in Appendix A. Based on this assumption, the total damage costs, C_t, was calculated using Equation 2.4

$$C_t = (C_d)\ (F) \qquad [2.4]$$

Where:

C_t = total damage costs
C_d = the average damage costs
F = damage frequency

Therefore, the average cost per trip of a pallet, A, is computed using Equation 2.5.

$$A = \frac{P + cb^S[(1+r)^U-1]}{U} \qquad [2.5]$$

Where:

P = purchase price of the pallet
c = economical coefficient
b = pallet design coefficient. b = 1.5 for lumber pallets
r = damage rate of the pallet
S = damage severity of the pallet

U = number of trips
A = average cost per trip

The average cost per trip after any number of uses can be determined using Equation 2.5 for those pallet designs for which their damage rate and severity have been determined. The number of trips at which the average cost per trip is a minimum is obtained by differentiating Equation 2.5 with respect to the number of use, U and setting to zero. This resulting equation must be solved by a process of successive approximations to yield the number of uses or the economic life of the pallet. A typical graphical solution is illustrated in Figure 2.1.

For a given pallet, the economical life can be calculated theoretically based on the known constants: (1) damage rate, R; (2) damage severity, S; and the (3) economic coefficient, c. The damage rate and damage severity were assumed only dependent on the pallets structural design and condition of use. Hence, Wallin and Whitenack (1984) proposed a model to predict the damage rate, R, and severity, S, from pallet design characteristics and handling environments.

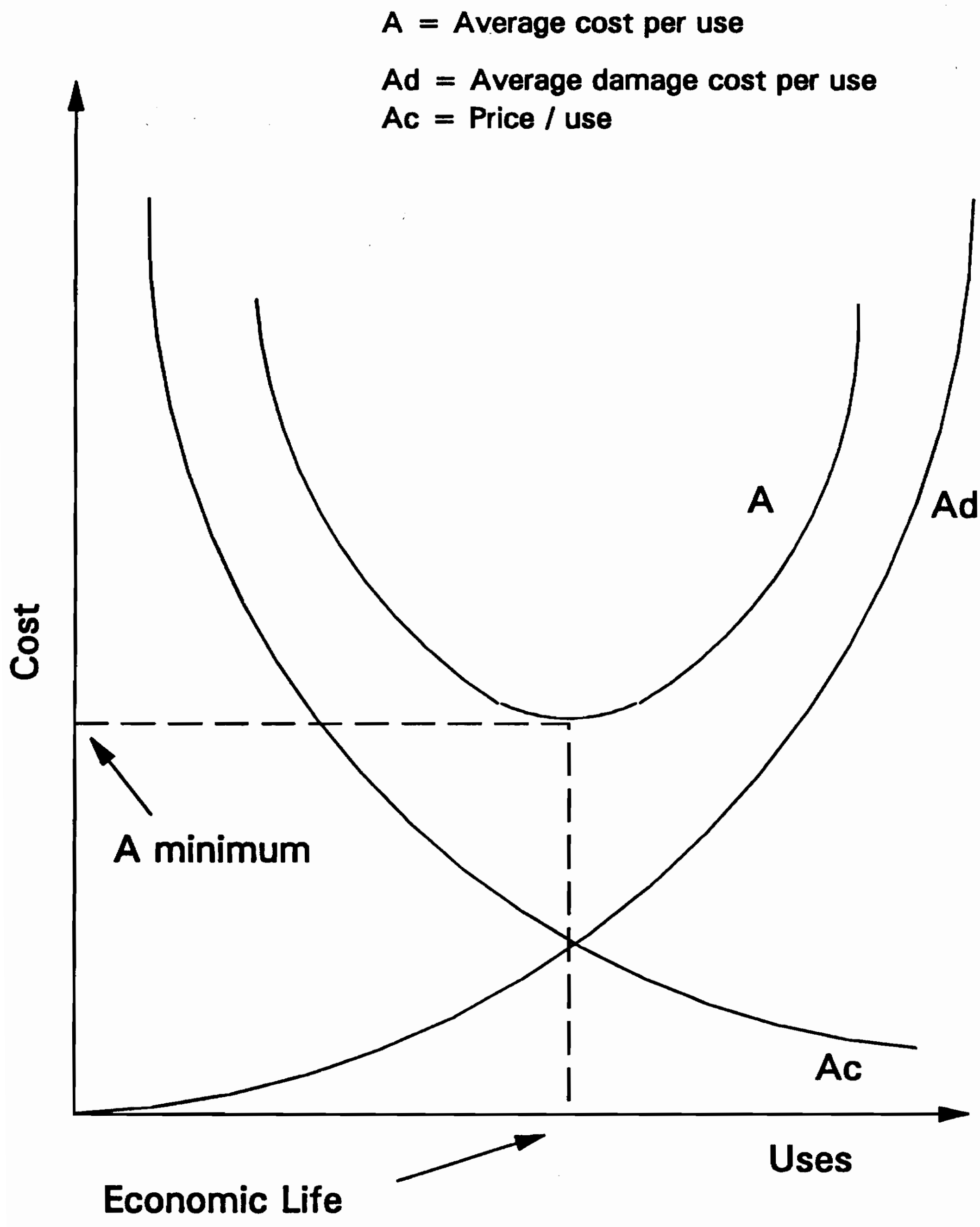


Figure 2.1 -- A typical graphical solution of economic life of a pallet

2.4.3 The Prediction of Damage Rate and Severity for Different Pallet Design

Previous research indicates that the durability of lumber deck pallets is the function of many characteristics, including species, shook grade, moisture content, nail type, and nailing pattern, loading characteristics, material handling procedures, and pallet structural configuration. Wallin and Whitenack (1984) derived several damage resistance factors that were intended to reflect the impact of pallet design characteristics and handling environment on the damage rate and damage severity. The calculated damage rate and severity were used as a measure of the increase or decrease in damage expected relative to the standard values for a designated high quality "base" pallet.

These factors are:

F(1) = Factor for joint separation resistance

F(2) = factor for joint torsional shear resistance

F(3) = factor for joint splitting resistance

F(4) = factor for pallet shook quality

F(5) = factor for selective placement

R(1) = factor for flexural strength of stringers

R(2) = factor for flexural strength of decks

R(3) = factor for deck construction

R(4) = factor for material handling environment.

The damage rate is computed using all of the above factors, while the damage severity is calculated using only the F factors. The exact relationships are shown in

Equations 2.6 and 2.7 for damage rate and damage severity, respectively.

$$R = (F(1)+1)(F(2)+1)\ldots(R(3)+1)(R(4)+1)(0.01) \qquad [2.6]$$

$$S = (F(1)+1)(F(2)+1)\ldots(F(5)+1)(2.0) \qquad [2.7]$$

Where 0.01 and 2.0 are the damage rate and damage severity of the "base" pallet design.

The durability model was derived from the data of lumber deck pallets and is currently used in the PDS for the durability prediction of lumber deck pallets. A detailed evaluation of the model is presented by in Appendix A and is the base for the experimental design for developing a durability procedure of panel deck pallets. The following conclusions are drawn based on the evaluation of the model.

1. The damage frequency was not the number of times that a pallet sustains damage, but the average number of damaged parts. The PEP study was not suitable to derive the relationship between damage frequency and the number of use since the number of uses for each pallet of the same type varied significantly. Therefore, the calculated damage rates for the PEP pallets were questionable.

2. The damage severity level assigned to each damage was not corespondent to the repair cost. According to Wallin's damage severity description, the cost of a

damaged part could exceed the cost to replace the part. That is not possible in reality.

3. It was not clear how the damage severity per pallet was calculated from damage severity levels of a pallet. The damage severity per pallet should be calculated based on the average repair cost of the pallet. However, the verification indicates that damage severity per pallet was incorrect for many pallet designs.

4. It was assumed that the damage severity per pallet was independent to the number of use. The verification indicates that the assumption seems valid. It must be pointed out, however, that the damage data is not valid for such verification because of the varied number of uses experienced by each pallet of the same type.

5. Eight damage resistance factors derived from the selected characteristics of a pallet design plus one factor of material handling environments were used to predict the damage rate, R, and severity, S. These factors reflected the increase or decrease of the R and S over that of the "base" pallet. Since, the calculated damage rate and severity of the PEP pallets were questionable, damage resistance factors were misleading.

6. The characteristics of pallet design used in the existing durability model were

limited to lumber deck pallets. Furthermore, many of the characteristics are interacted each other in terms of their effects on the damage rate and severity. Therefore, the model is very unstable for the future use.

According to Wallin's approach, the total damage cost of a pallet was related to damage rate and severity, which in turn were related to the pallet design. This approach involved many assumptions. Hence, the accuracy of the model is questionable. Therefore, a different approach will be used to relate the pallet design to the total damage cost in this study. The total damage cost as a function of the number of use for a pallet will be directly obtained from tests. Then, it is to find an equation using least square regression to fit the empirical relationship of the total damage cost and number of use. Finally, the predictability of the resulting regression coefficients for different pallet designs will be evaluated using multivariate regression analysis by selecting the appropriate characteristics of pallet design. In this way, the combined effect of the characteristics of pallet design on the total damage cost can be analyzed instead of estimating damage rate and severity separately.

3.0 EXPERIMENTAL PROCEDURES

To achieve the objectives of this study, various panel deck pallet designs were tested. These represent variations in style, materials, fastening etc. The pallets were tested using an accelerated simulation of an actual material handling system.

3.1 Accelerated Pallet Handling Test

Wood pallets provide the most economical handling system for handling a unit load. Pallets are generally used in the warehouse for storing various goods, in the truck for shipping products, and in the manufacturing plant for horizontally transporting products during manufacture. In these material handling systems, the pallets are lifted and moved using various material handling devices, such as pallet jacks, standle cars, forklifts, various conveyors, and palletizers for loading and unloading pallet.

These handling devices may damage pallets. The number of damages and their severity are dependent on, not only the pallet designs, but also the quality of the material handling system (Wallin, 1984). Low quality pallets and/or rough handling environments certainly cause more frequent and severer damage than high quality pallets and/or better material handling systems. Damages sustained by the pallets affect their serviceability by damaging product or slowing product movement. The damage at some point has to be repaired to keep the pallet serviceable. The cost of these repairs is the damage cost. To model the total damage cost of pallets, it is essential to identify the damages sustained in a particular material handling system. It is highly desirable to obtain such data from the in-field tests such as in the PEP study. However, the time to do these tests and the costs are prohibiting. An alternative is to set up a simulated material handling system.

3.1.1 Test Setup

A simulation called the "VPI Unit Load Material Handling "FASTRACK" (Figure 3.1) has been developed at the William H. Sardo Jr. Pallet and Container Research Laboratory at VPI&SU. This is a modification of a test used by the Proctor and Gamble Co. to simulate the use of pallets in the grocery dry goods industry (Cauffield and Fogler, 1989). The handling system includes the following stations:

A. Empty pallet storage area Empty pallets are stacked and stored in this area.

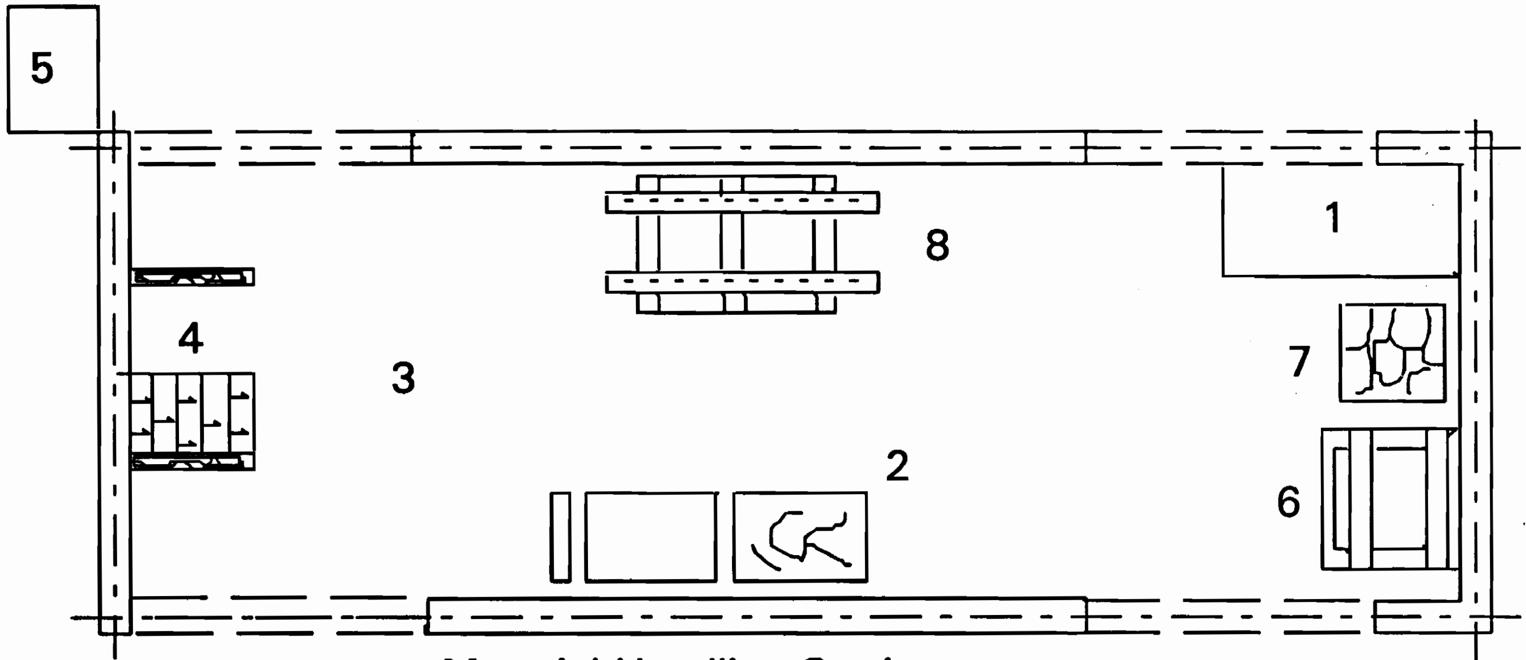
B. Palletizer This device serves as a platform to load or unload a pallet.

C. Staging Area This area is used for sluing and turning pallets so that the forklift can enter the pallet ends and sides and to transfer the pallet via pallet jack. The pallet is staged before and after entering the trailer.

D. Trailer This is a simulated 102" trailer opening with plywood sides. Pallets are moved in and out of one side of the opening to resemble confined space. Pallets are moved in and out endways and sideways.

E. Static Racked Storage This rack simulates warehouse rack storage. The span is adjustable.

F. Flow Rack This is a gravity feed flow rack which supports pallet on two sets of 5/8" wide rollers set 26" apart on center. The Pallet rolls on a 8 ft conveyor. The



Material Handling Stations

Station	Description	Station	Description
1	Empty pallet Storage	5	Transport simulator
2	Palletizer	6	Static rack storage
3	Staging area	7	Stack storage
4	Trailer	8	Flow rack storage

Figure 3.1 -- VPI "PasTrack" Material Handling System

incline is 1/25. Pallet travel is halted when the bottom leading edge deckboard impacts metal stops placed 26" apart.

G. Stack This simulates warehouse stacked storage of loaded pallets. The loaded pallet is placed on an irregular load of bagged fertilizer.

3.1.2 Test Cycles

The testing cycle in the study was intended to simulate the handling process of the U.S. dry grocery industries. This represents a varied handling environment. The unit load of 1500 Ibs was used. This represents the average load shipped by the U.S. dry grocery industries (Wallin, 1984). The test included idle pallet storage, palletizing, shipping, transport receiving, and three types of storage: static rack, flow rack and stacking. The test cycle is completed when the load is depalletized and the pallet is recycled. The handling devices used in the FasTrack include a 3,000-pound capacity counter-balanced fork lift and a 4,000-pound electric pallet jack.

The number of handlings a pallet received each cycle varied slightly depending on whether the pallet was two way, partial 4-way, or 4-way. A test cycle consisted of the following sequential operations:

1) Dropping an empty pallet from a 5 ft high stack (every 5 cycles);
2) Pick up an empty pallet and set down at the palletizer in the 40 direction of the pallet;
3) Transfer the load onto the pallet;

4) Pick up the loaded pallet from the 40" wide end and set down on the staging area;

5) Slue the pallet in the shipping staging area by fork lift so that it is picked up from the 48" side and loaded into the trailer;

6) Unloaded the unit load from the trailer and set it down in the receiving staging area;

7) Pick up the pallet again by electric jack and re-loaded into the trailer;

8) Unloaded the unit load from the trailer and set it down in the receiving staging area using the electric jack. If the pallet is full 4-way pallet, the step 7 is repeated using the side entry;

9) The unit load is lifted by fork lift and set down onto the static rack spanning the 48 inches pallet length;

10) The unit load is lifted from the rack and set on the top of stacked bags.

11) The unit load is lifted by forklift from the stacked storage and set down into a gravity feed flow rack. The loaded pallet rolls until it impacts the stops.

12) The unit load is lifted from the flow rack and placed against into the palletizer and the pallet is unloaded.

13) The empty pallet is lifted by forklift and returned to idle pallet storage.

3.1.3 Test Operation

The same operator conducted all tests. Pallets were inspected for damage prior to any tests, and again inspected after each cycle for damage. The damage data includes damage location, damage type (mode), factors responsible for the damage, and severity. No repair was conducted in this test. The test was terminated after 30 cycles or if the pallet was no longer functional due to damage. It should be noted that the pallets of different designs were not randomly tested. Tests were progressed by designs. This may result in some biases between designs because the driver may have handled the pallets differently through out the test.

3.2 Pallet Design Selection

Any pallet can be tested in the VPI "FASTRACK" system. In order to examine the effect of the pallet structural designs on the total damage costs, different pallet design were selected.

3.2.1 Pallet Classifications

All pallets in this study were 48"X40" with at least a top panel deck. Descriptions of the pallets tested are found in Table 3.1. Detailed specifications of these pallets are found in Appendix C.

Pallets in this study included two classes: stringer and block; three types: 2-way, partial 4-way, and full 4-way; and two styles: flush reversible and non-reversible pallets. All the reversible pallets were built with both panel decks, and no-reversible pallets contained panel top decks and lumber bottom deckboards. Two bottom lumber deck configurations for non-reversible pallet were used. There are unidirectional, and perimeter base. Figure 3.2 to 3.6 are the schematic diagrams of the 5 basic pallet configurations.

There were several reasons for selecting the different panel deck pallet designs. First, the greater the number of designs the more general the model for predicting durability. Second, different pallets are handled differently by the handling equipment. The damages sustained by these pallets may therefore differ. The third, the repair methods and related costs of these pallets may differ.

Table 3.1 -- Description of the panel deck pallet test designs

Pallet ID	Class	Type	Style[1]
Base design	Stringer[2]	Partial 4-way	Non-reversible
Design 1	Stringer	Partial 4-way	Non-reversible
Design 3	Stringer	Partial 4-way	Non-reversible
Design 2	Stringer	2-way	Reversible
Design 4	Stringer	2-way	Reversible
Design 7	Block[3]	Perimeter base	Non-reversible
Design 11	Block	Perimeter base	Non-reversible
Design 15	Block	Perimeter base	Non-reversible
Design 8	Block	Panel base	Reversible
Design 10	Block	Panel base	Reversible
Design 13	Block	Panel base	Reversible[5]
Design 6	Block	Unid. base[4]	Non-reversible
Design 9	Block	Unid. base	Non-reversible
Design 12	Block	Unid. base	Non-reversible

Note:

1 -- all the pallets are flush ends
2 -- all stringer pallets have 3 stringers
3 -- all block pallets have 9 blocks
4 -- unidirectional pallets with bottom deckboards parallel to the 40" direction
5 -- reversible pallets with panels in the top and bottom decks

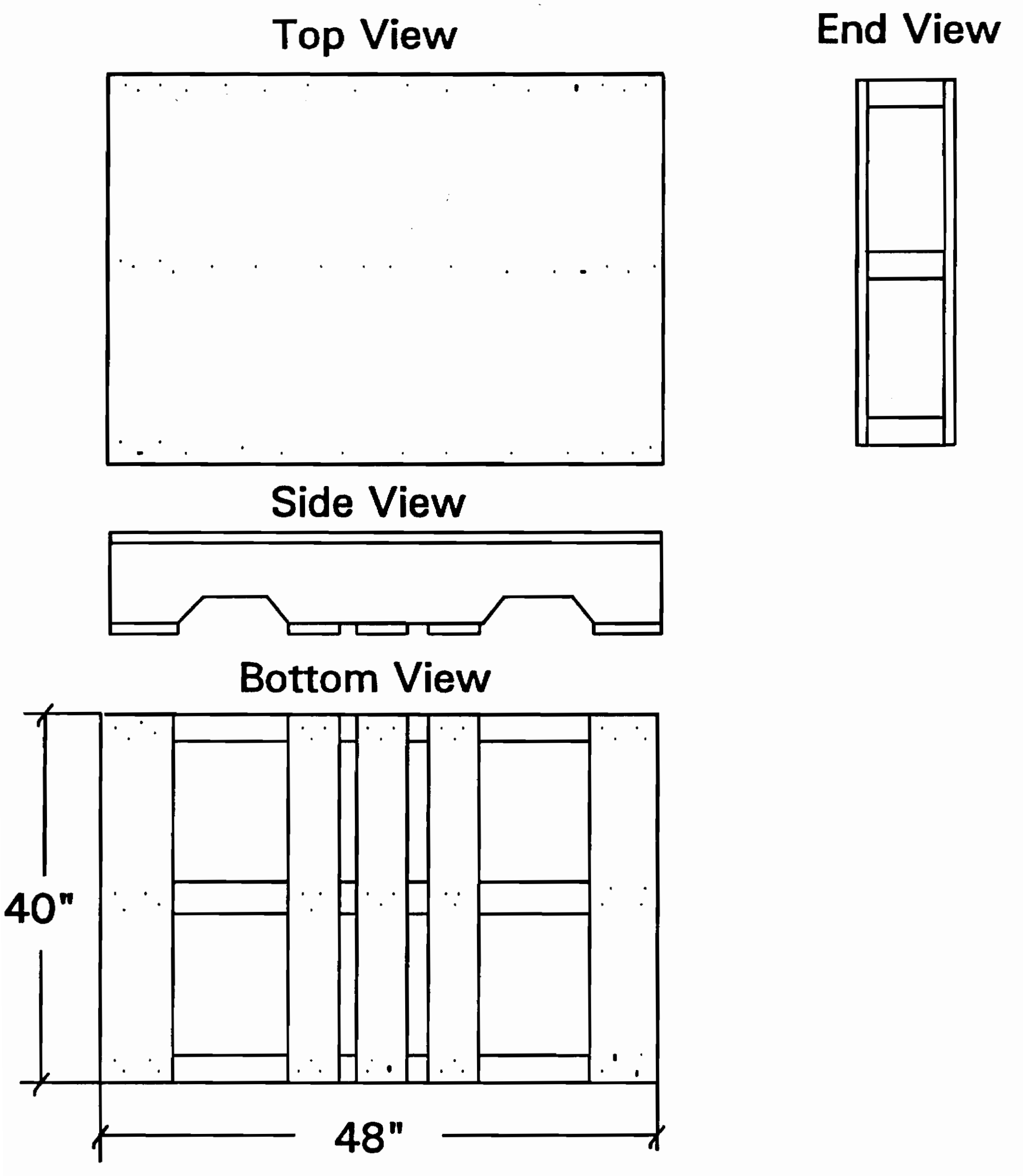


Figure 3.2 -- Schematic diagram of partial 4 way pallet designs (Base, D1, and D3)

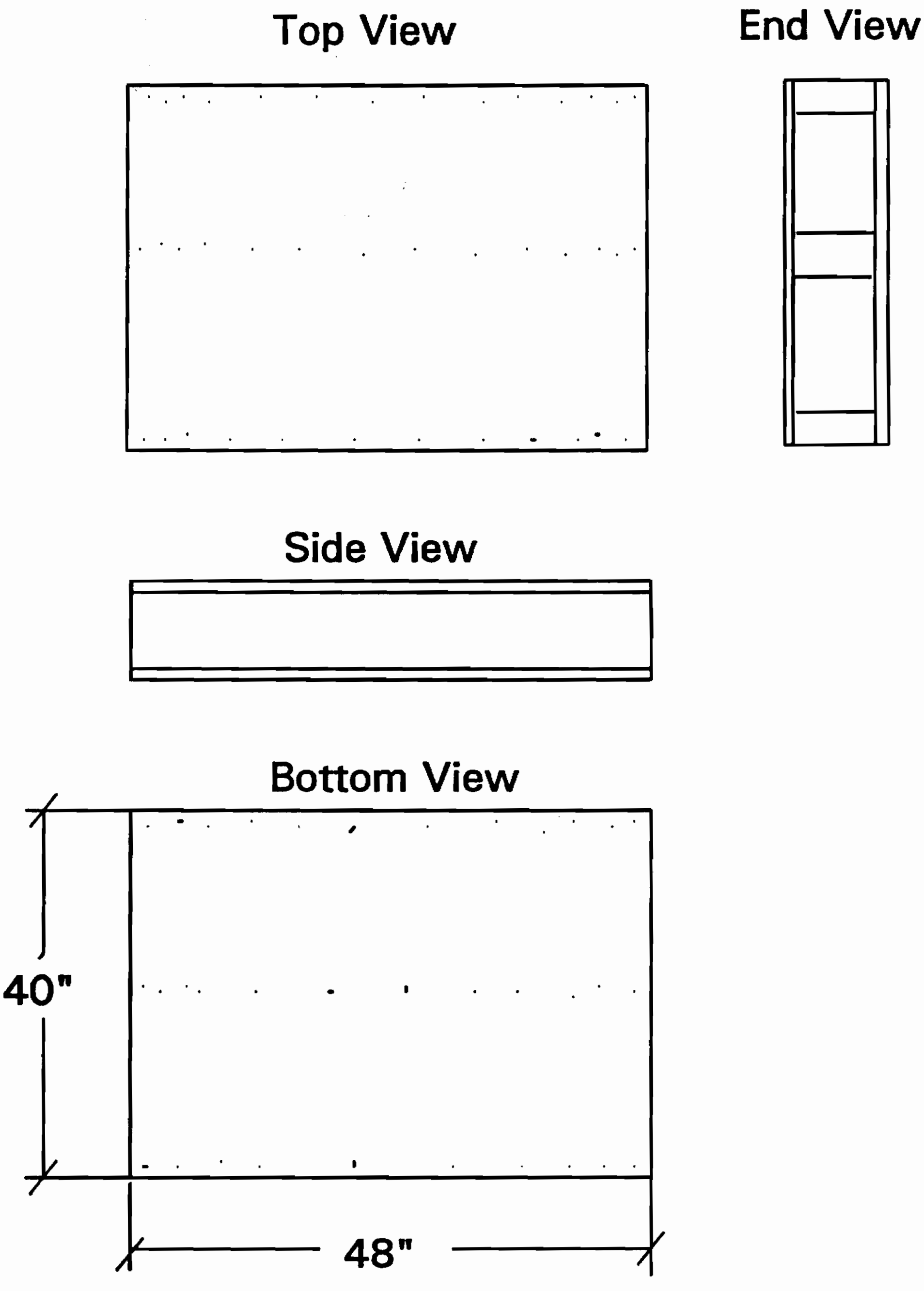


Figure 3.3 -- Schematic diagram of 2 way panel deck design for D2 and D4

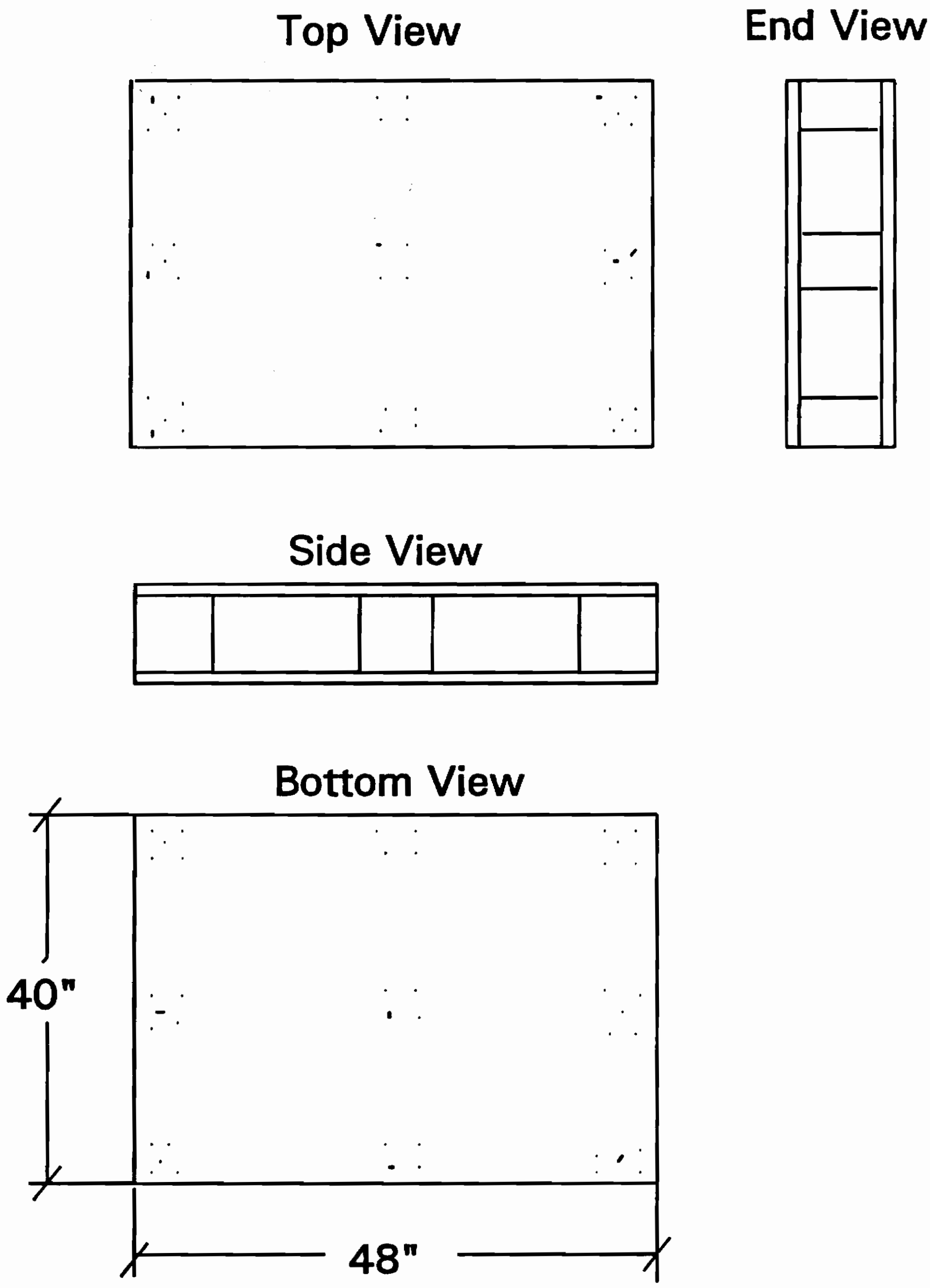


Figure 3.4 -- Schematic diagram of 4 way pallet design with both top and bottom panel decks (D8, D10, and D13)

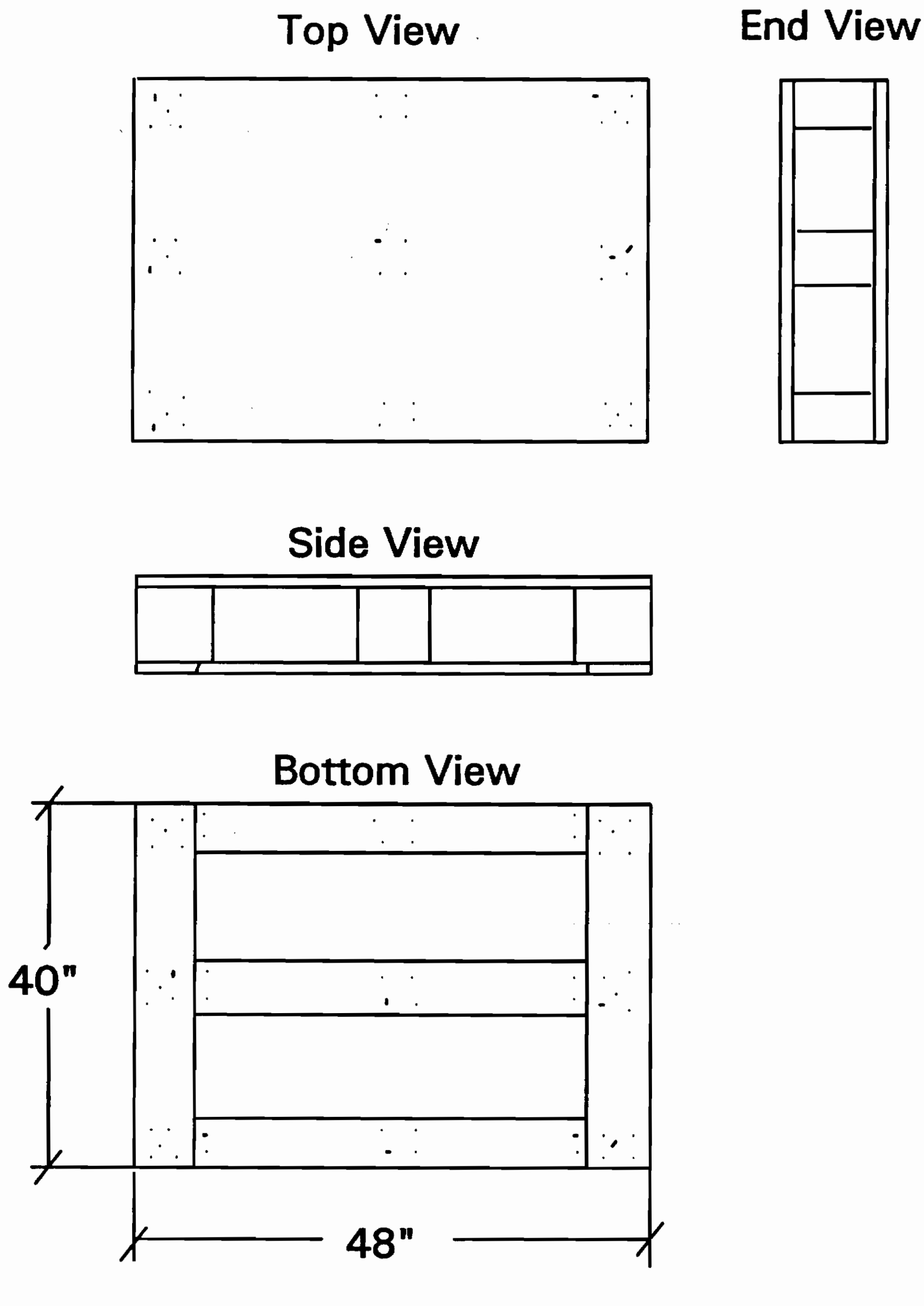


Figure 3.5 -- Schematic diagram of 4 way pallet design with perimeter bottom deckboards (D7, D11, and D15)

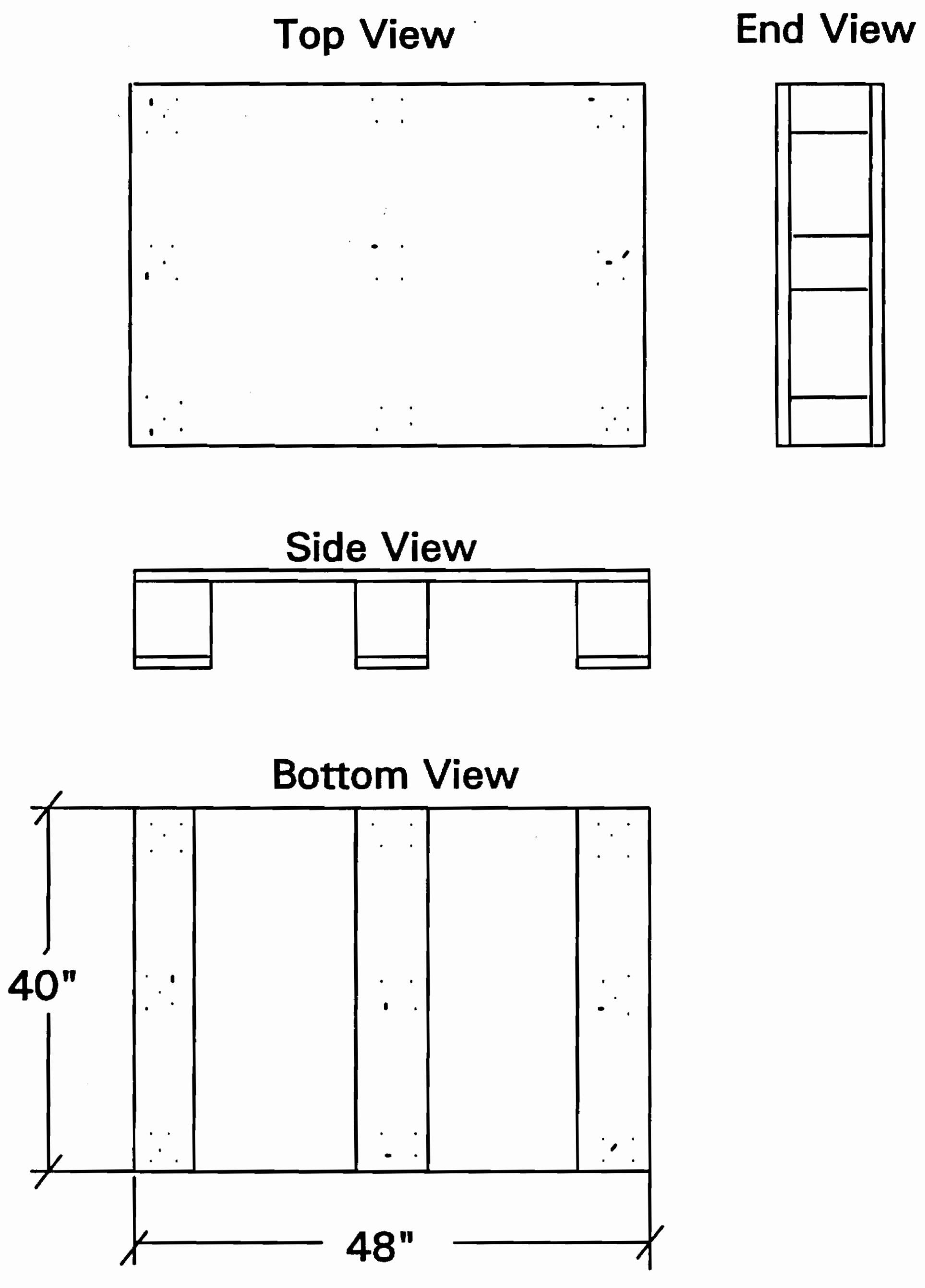


Figure 3.6 -- Schematic diagram of 4 way pallet design with unidirectional bottom deckboards (D6, D9, and D12)

3.2.2 Pallet Materials

The pallets were not only different in terms of the design, but also different in terms of materials used. Stringers and deckboards were different in their sizes and wood species, and panels were different in grade. Different block types were considered. It should be noted that although a range of pallet designs were tested, it is impossible to examine all possible combinations of pallet configurational designs. In this study, the emphasis was on range of structural designs which reflect those in use.

Structural panels Both structural plywood and OSB deck pallets were tested. APA specification contains three panel grades. These are APA Rated Sheathing (RS) , APA Rated Sturd-1-Floor (SIF), and APA Structural 1 Rated Sheathing (STR 1). Within each panel grade, different thickness ranging from 3/8" to 1-1/8", and different span ratings from 24/0 to 48/24 are specified (APA, 1991). It was decided that the input for structural panels in the durability model would conform to these specification which seems also to be used in non-APA rated products. In order to test the effect of a wide range of APA performance rated panels, all three APA panel grades were chosen. Within the grades, four span ratings and three thicknesses were selected as shown in Table 3.2.

Stringers there have been many previous studies on the effect of stringer species and size on pallet durability. Therefore, only two species groups, Southern Yellow Pine (S.P.) and mixed Eastern Oak (Oak), were used. These species groups represent a range of properties common to pallet construction. Within the two species groups, two different widths of stringers were used. These are 2-1/2" and 1-1/2". Furthermore, notched and non-notched stringers were used. The notches were 6" from the stringer ends, 1-1/2" deep, and 9" in length. A complete description of these stringers is found in Table 3.3.

lumber deckboards The effect of deckboard selection on the durability of lumber deck pallets have been extensively studied. The important properties of lumber deckboards, which affect the durability of pallets, were the wood species, grade, and size. Only S.P. and Oak were used in this study. The size of the lumber deckboards used in this study varied. For partial 4-way pallets, the dimension of all deckboards was 40" long, 5-1/2" wide, and 3/4" thick. For perimeter base, block pallets, the dimensions of two butted deckboards were either 40"X4"X3/4" or 40"X5-1/2"X3/4", and three center boards either 39"X4"X 3/4" or 37"X5-1/2"X3/4". In unidirectional base block pallets, the dimension of three deckboards was either 40"X4"X3/4" or 40"X5-1/2"X3/4'. The characteristics of the deckboards are found in Table 3.3.

Blocks Oak and laminated plywood blocks were used in the test pallets. All block pallets were 9 blocks including 6 end blocks and 3 center blocks. Two sizes of blocks were 6"X5-1/2"X4" and 5"X3-1/2"X3-1/2".

Nails Pallets were assembled using 5 different types of nails. A detailed description of these nails is found in Table 3.4.

Table 3.2 -- The characteristics of APA Performance Rated Structural Panels used in the test pallets

Panel type	Panel grade	Thickness[1]	Span rating[2]
Plywood	Rated Sheathing	3/8", 5/8", 3/4"	20/40, 24/48
	Structural 1	5/8", 3/4"	24/48
	Sturd-1-Floor	5/8", 3/4"	24, 40
OSB	Rated Sheathing	3/8", 5/8", 3/4'	20/40, 24/48
	Sturd-1-Floor	5/8", 3/4"	24, 40

Note:

1 -- the thickness for each panel grade

2 -- the span rating for each panel grade, not for each thickness combination (i.e. panels with different thickness may have the same span rating)

Table 3.3 -- Characteristics of stringers and lumber deckboards used in test pallets

Shook[1]	Species	Dimension	Grade[2]
Stringer[3]	Southern Yellow Pine (S.P.)	48"X2-1/2"X3-1/2"	class 3
		48"X1-1/2"X3-1/2"	class 3
	Oak	48"X2-1/2"X3-1/2"	class 3
		48"X2-1/2"X3-1/2"	class 3
Deckboard	Southern Yellow Pine (S.P.)	40"X5-1/2'X3/4"	class 3
		37"X5-1/2"X3/4"	class 3
		40"X4"X3/4"	class 3&4
	Oak	40"X4"X3/4"	Class 3&4
		37"x4"X3/4"	class 3&4

Note:

1 -- all lumber parts were green at assembly
2 -- grades were according to the PEP grading rules (Appendix D)
3 -- stringers were either plain or notched with the standard notch dimension (i.e. 6" from end, 12" long, and 1-3/4" deep)

Table 3.4 -- Characteristics of fasteners used in assembly of the test pallets

VPI Fastener No.	Nial Type	Nail Length (inches)	Thread Length (inches)	Thread Daim. (inches)	Head Diam. (inches)	Wire Diam. (inches)	Number Helix	Number Flutes	Mibant Angle (degrees)
2496 (A)	Helical	2.25	1.38	0.133	0.285	0.111	6.9	4	25
2626 (B)	Helical	1.97	1.31	0.144	0.284	0.121	6.5	4	16
2348 (C)	Helical	2.25	1.63	0.132	0.285	0.122	5.0	4	39
3047 (D)	Annular	2.06	1.44	0.133	0.290	0.120	N/A	29[1]	34
3333 (E)	Helical	2.25	1.50	0.137	0.280	0.120	6.0	4	33
2991 (F)	Helical	2.00	1.58	0.134	0.262	0.113	6.0	4	47

Note:

1 -- number of rings for annular nail

3.2.3 Pallet Construction

One hundred pallets representing fifteen panel deck designs were tested. All pallets were fabricated at the Pallet and Container Laboratory at VPI&SU except for design 10 and 15. Design 10 and 15 were the pallets which were left over from previous tests in the Pallets and Container Lab. All structural panels with APA grade mark were donated by Georgia-Pacific Corporation. Lumber deckboards, stringers, and blocks were donated by the Williamsburg Millwork Corporation. The panels were cut into 48 inches by 40 inch sections with strength axis of panel parallel to 48" direction. The grades of lumber pallet parts were determined after the fabrication of the pallets. The grading criteria is described in Appendix D. The "base" design included 25 replications and the other designs were 5 replications each.

This was not a complete factorial experimental design. The detailed specifications of pallet designs tested in this study are found in Appendix C.

4.0 RESULTS AND DISCUSSIONS

4.1 Pallet Damage

All damage to each part of each pallet was recorded after each test cycle. Damage levels were measured numerically in order to assess severity. The damage modes in lumber components, either stingers or deckboards, were splits, broken parts, cracks, or joint failure. The damage modes in panels were edge dent, veneer torn off, panel crack, or joint failure. In order to simplify the analysis, only four damage modes were used in this study to describe all types of damages observed in the pallets tested. There were cracks, missing parts, breaks, and joint failure. They were defined as bellow.

<u>Cracks</u> Any separation within a pallet component extends in any direction of the component, and the resulting portions are still in place. The separation can pass though joints, which render the joints at least partially ineffective. Cracks can be found in lumber deckboards, stringers, and blocks. Cracks in panels were defined as veneer separation. The cracks in the lumber deckboards and stringers are illustrated in Figure 4.1.

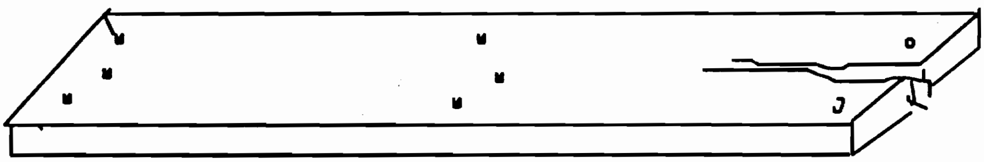
<u>Missing Parts</u> A missing part is a portion of a component on a complete component that has been removed. This damage can be found in all pallet components. A missing part in a panel deck is either edge dent or veneer torn off. A missing part is measured by its length and width. Figure 4.2 illustrates missing parts in deckboards and stringers, respectively, and Figure 4.3 illustrates missing parts in a panel which includes

edge dent and veneer torn off.

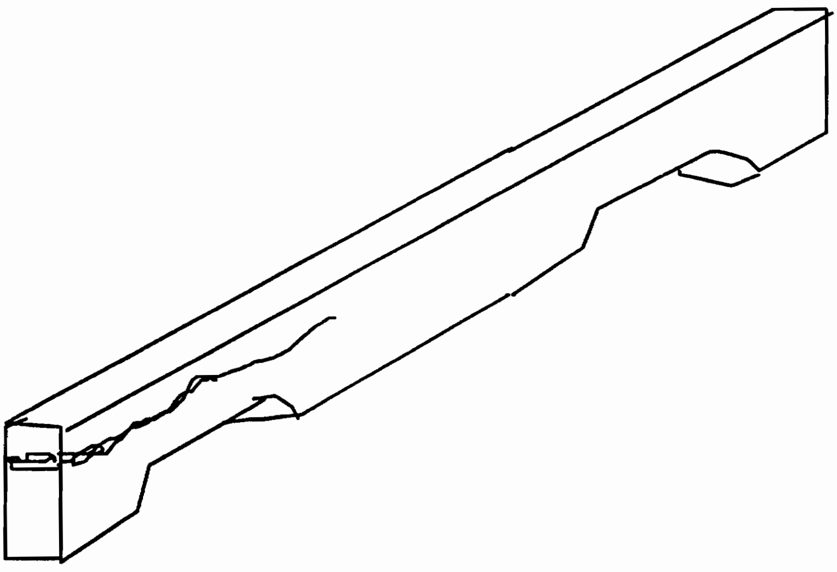
Breaks A break is a complete separation of a component either cross the full width or full length. Unlike a crack, the resulting portions of a break are no longer held together. A break can be found in all shook components. A break is also measured by its length and width. Figure 4.4 illustrates breaks in a deckboard, stringer, and panel.

Joint Failure Joint failure is defined as either nail head popping or nail head pull through, which causes a reduction in the ineffectiveness of the joint. Nail popping results from nail shank withdrawal from the fastening member. the level of damage depends on the number of fasteners affected. Figure 4.5 illustrates nail popping and nail head pull through of a panel.

Generally, cracks occurred first, and then progress to either a part missing or component broken. Nails and lumber defects predominantly contributed to the split at deckboards, and forklift and pallet jack mainly contributed to the cracks at stringers or blocks. The handling and rack support conditions many times caused the joint failure.

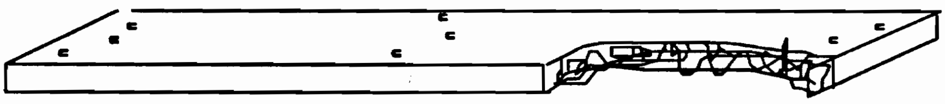


a. Crack in lumber deckboard

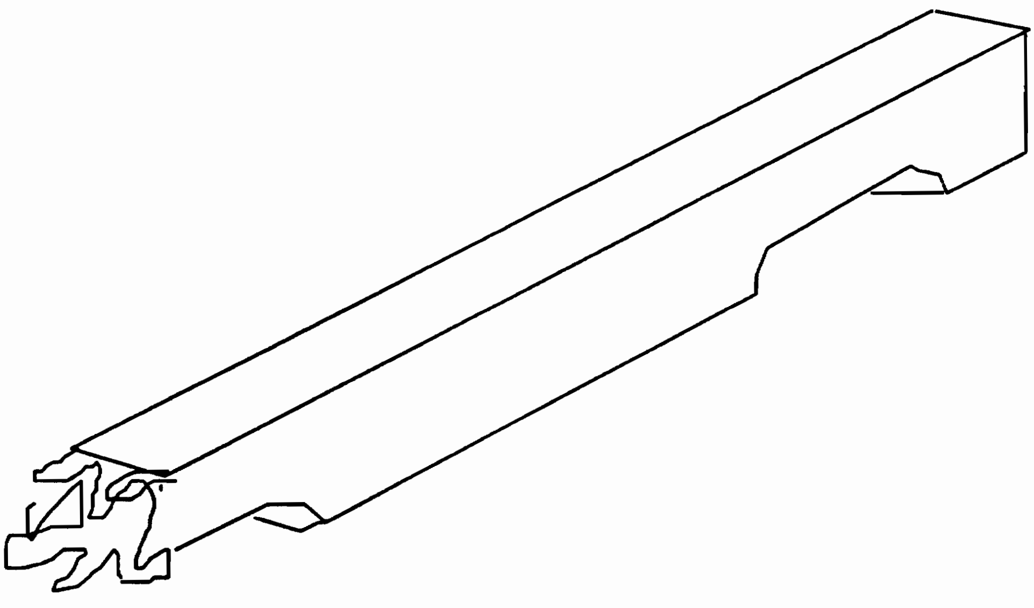


b. Crack in stringer

Figure 4.1 -- Examples of "sracks" in lumber deckboards and stringers

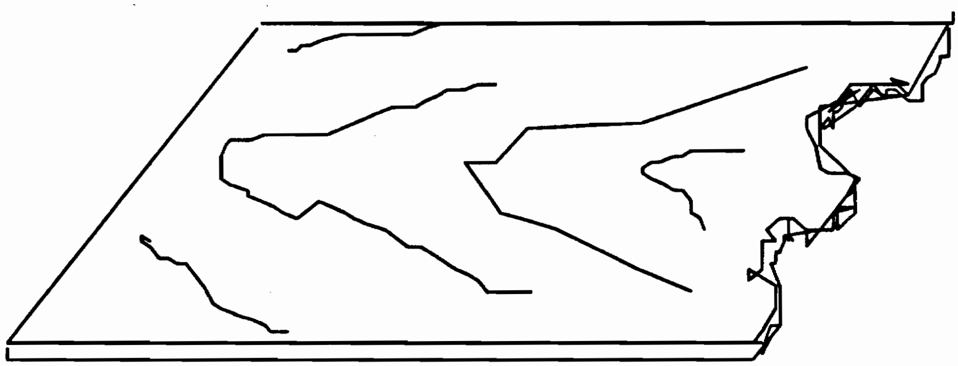


a. Missing part in deckboard

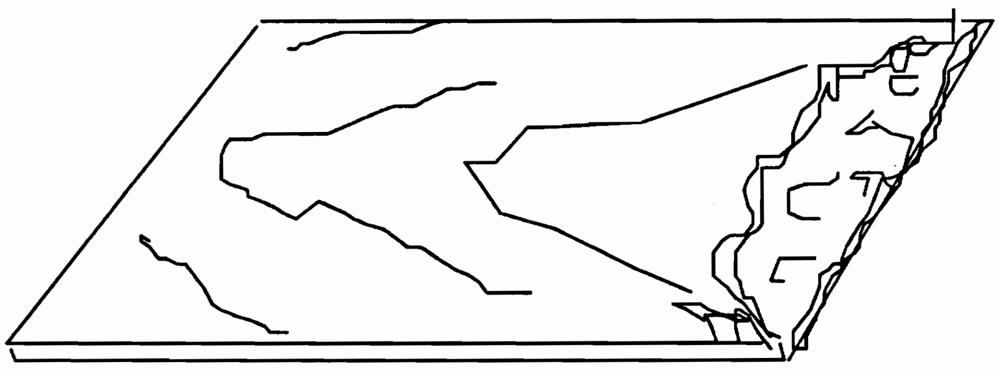


b. Missing part in stringer

Figure 4.2 -- Example of missing parts in deckboards and stringers

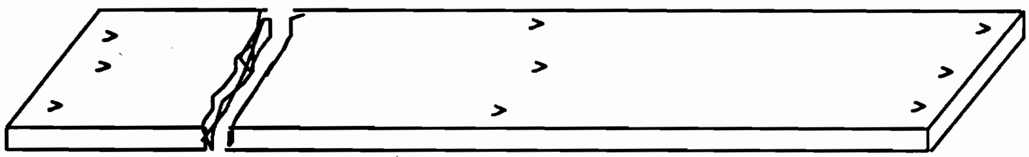


a. Edge dent

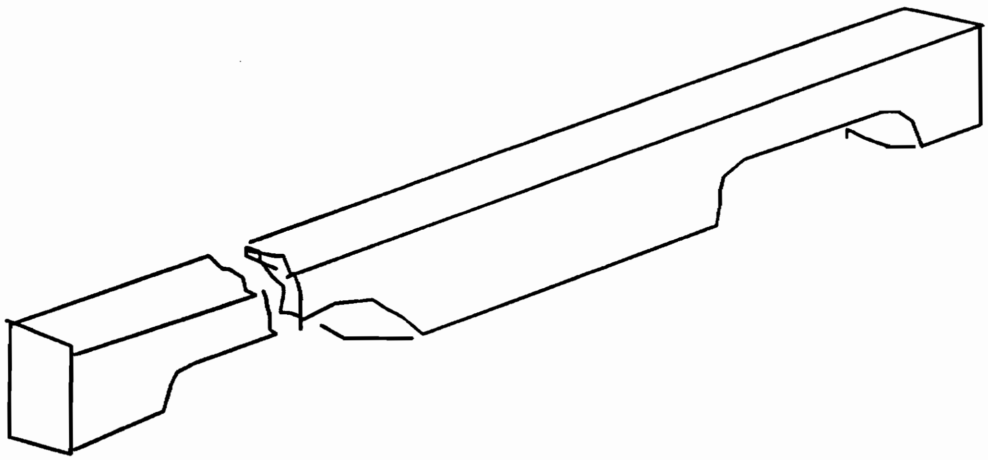


b. Veneer torn off

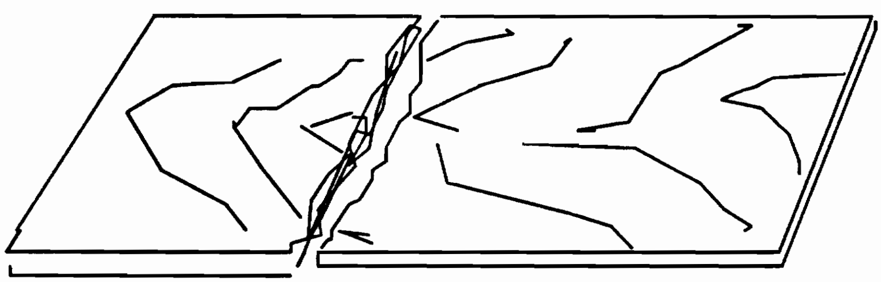
Figure 4.3 -- Example of missing parts in structural panels



a. broken deckboard



b. Broken stringer



c. Broken plywood deck

Figure 4.4 – Examples of breaks in deckboards, stringers, and panels

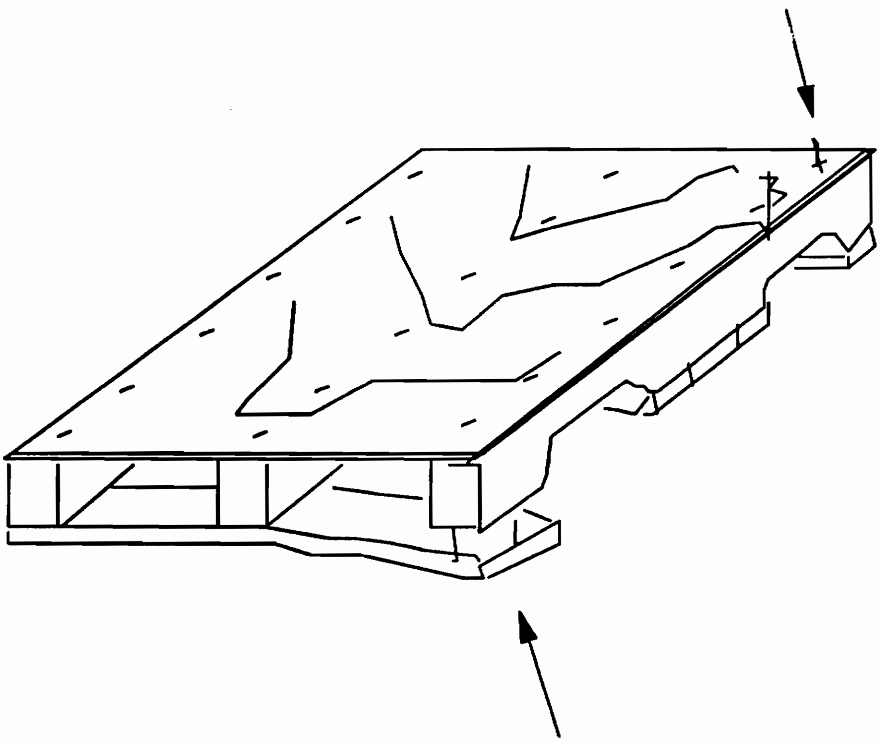


Figure 4.5 -- Example of failure at connections

4.2 Damage Severity

In order to facilitate the analysis, each damage incident was designated a severity level which was related to the cost of repair. Damage severity level for each damage incident was assigned using a program written in Statistical Analysis System (SAS). Figure 4.6 is a schematic diagram showing how damage was assigned a severity level. From each damage record, the program compared the damage mode with a repair criterion and a repair decision is made. Associated with each repair is an estimated repair cost.

4.2.1 Repair Requirement

As have been discussed, any one or combinations of the four damage modes can be found at any part of a pallet. The criteria and method of repairing a damaged part depended on the location of the part and the damage mode. The damage repair requirements and methods are summarized below. This criteria is based on the currently employed published repair procedures (CPC, 1989, NWPCA, 1992, CHEP USA, 1990). It is worth noting that no repair was actually performed in the pallets tested.

4.2.1.1 Repair of broken parts:

Deckboards: In this study, it was assumed a broken deckboard was replaced with a like new component. The deckboard was replaced with a like deckboard of the same size and quality, such as a chamfered deckboard (NWPCA, 1992).

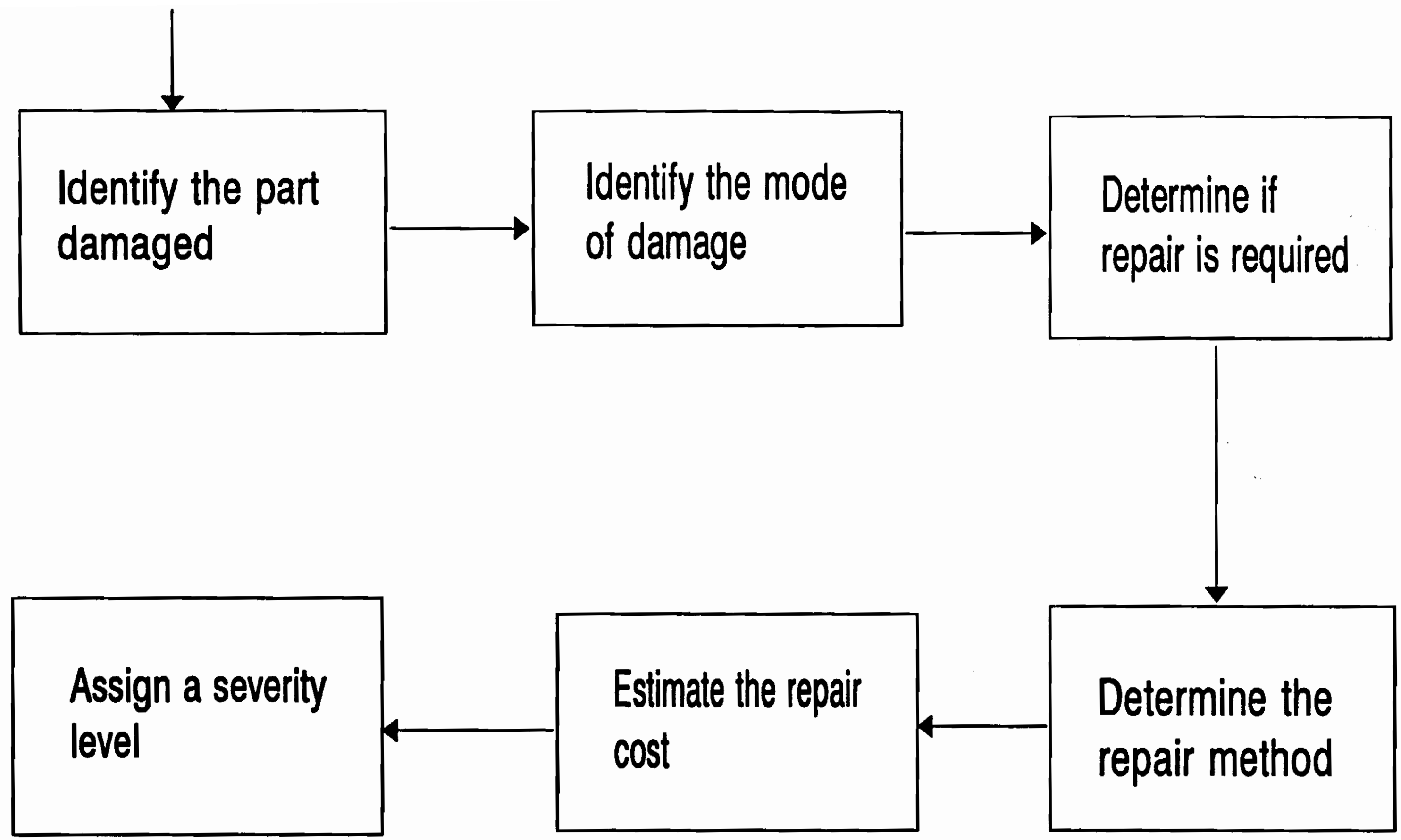


Figure 4.6 -- Method of assigning damage level or severity to pallet parts

Stringers: It was assumed a broken stringer was replaced in accordance with the methods described in the Uniform Voluntary Product Standard for Wood Pallets (NWPCA, 1992). Edge stringer replacement and center stringer replacement are treated separately because of the different repair costs.

Blocks: A broken block with more than the half of its cross section missing is required to be replaced.

Panels: A broken panel is repaired using the same grade and thickness of panel. To be consistent, all broken panels are assumed to be replaced with the same grade and thickness part.

4.2.1.2 Repair of cracks

Deckboards: Any cracked board with a crack length longer than the half of the board's length is replaced.

Stringers: A stringer with crack up to 5" long is assumed to be with a short block. A crack from 5" to 1/2 length is repaired with a 1/2 stringer, and a crack more than 1/2 stringer is repaired with a full companion stringer.

Blocks: A cracked block with more than 3/4 of the cross section missing is replaced.

Panels: When a veneer separation in length is more than 1/2 the width it is repaired with a lead board which has the same thickness as the panel.

4.2.1.3 Repair of missing parts

Deckboards: A missing deckboard is assumed to be replaced with a new one. A missing part with more than 1/2" wide by more than longer than half of the board length (M1) is replaced with a new one. A part with 1" wide by quarter of the board length missing (M2) is replace with a new one. A part with a 2" wide by 5" long missing (M3) is replaced with a new one.

Stringers: A stringer with 1-1/2" in wide by 5" long section missing is replaced with a new one. An edge stringer (M1) and center stringer (M2) are treated separately because of their different repair costs.

Panels: The missing part is considered as edge dent. The edge dent more than 3.5" in depth and more than 5" in width (M1) is repaired by adding a lead board with the same thickness of the panel.

Blocks: A block with more than one quarter of its cross section missing is replaced with a new one. Misaligned blocks require realignment.

4.2.1.4 Repair of joints

Nail popping: Whenever the nail popping occurs, the component is renailed. New nails are considered in this study for renailing.

Nail head pull through: Renailing is required with new nails.

4.2.2 Repair Costs

A survey of pallet repair cost was conducted by Mr. Englbert Schulte in 1991. 18 companies were surveyed. The pallets included stringer pallets and block pallets with either lumber deckboards or panel decks. Repair costs by damaged part and repair methods are summarized in Table 4.1 (Schulte, 1992).

The survey didn't include the repair costs for block and panel damages. The methods and corresponding costs of block and panel repairs were estimated based on the following assumptions. These are a modification of cost estimates made by the Proctor and Gamble (Cauffied and Fogler, 1989).

1) Hourly wage rate	- $8.00
2) Benefits of 30%	- $2.40
3) Lumber deck cost	- $0.30
4) Panel deck cost	- $7.40
5) Block cost	- $0.30
6) Stringer cost	- $0.66
7) Nail cost	- $0.015
8) Lumber deck repair/hr.	- 25
9) Panel deck repair/hr.	- 25
10) Stringer repair/hr.	- 20
11) Block repair/hr.	- 37

1. Lumber deckboard replacement cost:

1) Wage = 10.40 X (1/30) =	$ 0.35
2) Material: deckboards	$ 0.30
nails (11)	$ 0.17

Total Cost/Deck repl. =	$ 0.82

2. Panel deck replacement cost:

1) Wage = 10.4 X (1/25) =	$ 0.40
2) Material: Panel =	$ 6.40

Table 4.1 -- Estimated repair costs by damaged part and repair method[1]

Damage components	Repair method	Repair cost
Lumber Deckboards (Stringer pallets)	a) Renail joint	$ 0.36
	b) Replace missing part	$ 0.58
	c) Remove and replace	$ 0.62
Lumber Deckboards (Block Pallets)	a) Renail Joint	$ 0.24
	b) Replace missing part	$ 0.64
	c) Remove and replace	$ 0.82
Stringers	a) Add short block	$ 0.40
	b) Add long block	$ 0.47
	c) Add half stringer	$ 0.50
	d) Add full stringer	$ 0.78
	e) Add metal plate	$ 0.53
	f) Replace outside stringer	$ 1.10
	g) Replace inside stringer	$ 1.16
Blocks	a) Realignment	$ 0.43
	b) Replace block	$ 0.70
	c) Insert blocks	$ 1.27
Panels	a) Renail joint	$ 0.35
	b) Add lead board	$ 0.82
	c) Add two lead boards	$ 1.64
	d) Replace	$ 7.34

Note:

1 -- data for lumber deckboards and stringers from the results surveyed by Schulte (1992), for blocks and panels are estimated based on P&G Co. (1989)

Nails(36)	=	$ 0.54

Total cost/panel rep.	=	$ 7.34

3. Stringer replacement cost:

1) Wage = 10.4 X (1/20)	=	$ 0.52
2) Material: Stringer	=	$ 0.66
Nails(17)	=	$ 0.25

Total cost/Str. Rep.	=	$ 1.43

4. Block replacement cost:

1) Wage = 10.4 X (1/37)	=	$ 0.28
2) Material: block	=	$ 0.30
Nails (8)	=	$ 0.12

Total cost/block rep.	=	$ 0.70

4.2.3 Severity Level Codes

The survey of pallet repair indicated that repair costs are dependent on the repair method used. The damage costs for all the damage modes which require repair for each component were determined and shown in Table 4.2. This table indicates the range of repair costs for different pallet parts. The repair costs for deckboards were from $0.36 to $0.81. The repair costs for stringers ranged from $0.40 to $1.16. A very high repair costs is associated with panel replacement.

Since the damage severity level was used to relate a damage to its repair cost, it was necessary to combine the damage costs for all the damages regardless which component. Therefore, the repair costs in Table 4.2 were sorted in the descended order. The sorted

Table 4.2 -- Estimated repair costs by pallet part, damage mode, and repair method

Pallet Part	Damage mode[1]	Repair method[2]	Costs
Deckboard	Joint failure	Renailing	$0.36
	Break (stringer pallet)	Replace	$0.62
	Break (block pallet)	Replace	$0.81
	Missing part	Replace	$0.81
	Crack	Replace	$0.81
Stringer	Missing part	Short block	$0.40
	Crack 1	Short block	$0.40
	Crack 2	Half runner	$0.40
	Crack 3	Full runner	$0.79
	Missing part (Edge)	Replace	$1.10
	Missing part (Center)	Replace	$1.16
	Break (Edge)	Replace	$1.10
	Break (Center)	Replace	$1.16
Block	Joint failure	Realignment	$0.43
	Crack	Replace	$0.70
	Break	Replace	$0.70
Panel	Joint failure	Renailing	$0.36
	Missing part (M1)	Add lead board	$0.81
	Missing part (M2)	Add lead boards	$1.62
	Crack	Add lead board	$0.81
	Break	Replace	$7.34

Note:

1 -- all the damages exceed the requirement for repair

2 -- repair methods are slightly different among pallet repair companies. It is assumed methods are the same in this study

repair data is shown in Table 4.3. The whole range of repair costs for all pallet components were from \$0.36 to \$6.40. In order to simplify the analysis, the damage costs were partitioned into 5 classes ranging from 6 to 10 which were defined as damage severity levels. The costs of severity level of 6 range from \$0.36 to \$0.43 with the average of \$0.41, severity level of 7 ranged from \$0.62 to \$0.70 with average of \$0.67, and so on. From Table 4.3, it can be seen that the highest damage severity for deckboards is 8 and the highest damage severity of panels is 10. Not all damage severity levels were applicable to all components. This is different from the PEP study. In the PEP study, a damage can be any one of the severity levels defined. This is not true because the repair costs of a deckboard never exceed the cost of its replacement.

All the damage levels in Table 4.3 require repair. In order to cover the damages which do not need repair, the lower damage severity levels were defined, ranging from 1 to 5. The detailed descriptions of all severity levels used in this study are found in Table 4.4.

Table 4.3 -- Damage severity codes and groupings based on repair costs by pallet part and damage mode

Pallet part	Damage mode	Repair cost	Severity
Deckboard	Joint Failure	$0.36	6 ($0.41)
Panel	Joint failure	$0.36	
Stringer	Missing part (M1)[1]	$0.40	
Stringer	Crack (C1)[2]	$0.40	
Stringer	Crack (C2)[2]	$0.50	
Block	Joint failure	$0.43	
Deckboard	Break (stringer pallet)	$0.62	7 ($0.67)
Block	Crack	$0.70	
Block	Break	$0.70	
Stringer	Crack (C3)[2]	$0.79	8 ($0.92)
Deckboard	Break (block pallet)	$0.81	
Deckboard	Missing part (M1)[3]	$0.81	
Deckboard	Missing part (M2)[3]	$0.81	
Deckboard	Missing part (M3)[3]	$0.81	
Panel	Missing part (M1)[4]	$0.81	
Panel	Crack	$0.81	
Stringer	Missing part (M2)[1]	$1.10	9 ($1.43)
Stringer	Break (Edge)	$1.10	
Stringer	Missing part (Center)	$1.16	
Panel	Missing part (M2)	$1.62	10 ($4.00)
Panel	Break	$6.40	

Note:

1 -- Missing part for stringer with 1-2/" wide and 5" long: M1 -- edge stringers; M2 -- center stringers

2 -- Cracks for stringers: C1 -- up to 5" long; C2 -- 5" to 1/2 of stringer length; C3 -- more than 1/2 of stringer length

3 -- Missing part for deckboards M1 -- 1/2" wide; M2 -1" wide; M3 -- more than 2" wide

4 -- Edge dent of panel with 3-1/2" in depth

Table 4.4 -- The damage descriptions of 1 to 10 severity levels defined in this study

Severity	Pallet part	Description of the damage
1 ($0.06)	Deckboard	Cracks less than 3 inches long, which extend through one nail. Missing parts less than 1/2 inches wide and less than 5 inches long, which extend at most one nail.
	Stringer	None allowed.
	Block	Any splits and missing part which do not affect any nail.
	Panel	None allowed.
2 ($0.08)	Deckboard	Cracks 3 to 6 inches long. Missing part less than 1/2 inch wide and to 10 inches long, which extend at most one nail.
	Stringer	Splits less than 3 inches long, which does not pass through notches.
	Block	Any split and missing part which do not affect more than one nail.
	Panel	Edge dents less than 1/2 inch in depth. Separations do not extend 5 inches wide.
3 ($0.12)	Deckboard	Cracks 6 to 10 inches long. Missing parts less than 1/2 inch wide and 5 to 10 inches long, or less 1 inch wide and 5 inches long.
	Stringer	Splits less than 3 inches long, which does not extend notches. Missing parts less than 1/2 of the cross section and less than 3 inches long.
	Block	Cracks less than 3/4 of the cross section. Missing parts less than 1/2 of the cross section.
	Panel	Edge dent 1/2 to 1 inch deep and less than 20 inches long. Separations do not extend 10 inches long.

Table 4.4 Continued

Severity	Pallet part	Description of the damage
4 ($0.19)	Deckboard	Cracks 10 to 20 inches long. Missing parts less than 1 inch wide and 5 to 10 inches long, or 1 to 2 inches wide and less than 5 inches long.
	Stringer	Splits 3 to 6 inches long, which does not extends notches. Missing parts less than 1/2 of the cross section and 3 to 5 inches long.
	Block	Separation through its height, which does not affect nails.
	Panel	Edge dent 1 to 2 inches. Veneer torn off 5 inches wide and 5 inches long, which result in less than 1/5 of the panel thickness reduction.
5 ($0.28)	Deckboard	Missing part 1/2 to 1 inches wide and 10 to 20 inches long, or 1 to 2 inches wide and 5 to 10 inches long.
	Stringer	Cracks 6 to 10 inches long. Missing part 1/2 to 3/4 of the cross section and 3 to 5 inches long.
	Block	Separation through its height, which pass through one nail.
	Panel	Edge dent 2 to 3 inches deep. Veneer torn off 5 to 10 inches wide and 5 to 10 inches long, which result in less than 1/5 of the panel thickness reduction.
6 ($0.41)	Deckboard	Any damage ranging from level 1 to 5, which causes one joint completely ineffective.
	Stringer	Missing part less than 1/2 of its cross section and larger than 5 inches long, or 1/2 to 3/4 of its cross section and 3 to 5 inches long. Cracks 10 to 24 inches long.
	Block	Any damage ranging from 1 to 6 plus the joint ineffective.
	Panel	Any damage ranging from 1 to 5 plus 1 to 2 joints ineffective.

Table 4.4 Continued

Severity	Pallet part	Description of the damage
7 ($0.67)	Deckboard	Breaks cross full width or full length for stringer pallets. Any damage ranging from 1 to 5 plus more two joints ineffective. A complete part missing.
	Stringer	Not applicable.
	Block	Break which more than 1/2 of its part. Crack which more than 3/4 of its part.
	Panel	Not applicable.
8 ($0.92)	Deckboard	Break cross full width or full length for block pallet. Missing part 1/2 to 1 inch wide and more than 20 inches long, or 1 to 2 inches wide and more than 10 inches long, or more than 2 inches wide and more than 5 inches long.
	Stringer	Missing part 1/2 to 3/4 of its section and 5 to 24 inches long, or more than 3/4 of its cross section and more than 5 inches long. Crack more than 24 inches long.
	Block	Not applicable.
	Panel	Edge dent 2 to 4 inches deep. Separation through thickness which extends more 20 inches long.
9 ($1.43)	Deckboard	Broken stringer cross section. Missing part more than 3/4 of its cross section and more than 5 inches long, or 1/2 to 3/4 of cross section and more than 24 inches long.
	Stringer	Not applicable.
	Block	Not applicable.
	Panel	Not applicable.
10 ($4.00)	Panel	Broken in the middle.

4.2.4 The Relationship Between Damage Costs and Severity Level

The actual damage costs were only available for those severity levels which require repair as shown in Table 4.3. The severity levels which do not require repair were also assigned a monetary value. This was accomplished by a least square regression of severity levels from 6 to 10 and then extrapolating the relationship to severity levels from 1 to 5.

Equation 4.1 was derived by regression and relates the damage cost to severity level.

$$LN(C) = a + bS \qquad [4.1]$$

where:

S = damage severity level
C = repair cost of severity level S
a = -3.303
b = 0.406

Equation 4.1 was extrapolated to the severity levels from 1 to 5. The damage costs for the severity levels were calculated using Equation 4.1, shown in Table 4.4. Equation 4.2 was the transformation of Equation 4.1. This was the same form which the existing model used to calculate the damage costs based on the damage severity. However, the description of damage severity in this study was different from that used in PEP study. The damage cost calculated based on Equation 4.2 is directly related to the repair costs unlike the current model which is evaluated in Appendix A.

$$C = ab^S \qquad [4.2]$$

Where:

C = damage cost
S = damage severity
a = 0.0368
b = 1.5008

4.3 Total Damage Cost, C_t

It is essential to calculate the total damage cost of a pallet at any time during use. The damages for one of the base pallet design tested is found in Table 4.5. The base pallet is a non-reversible, partial 4-way, 3-stringer pallet with the top deck of APA Rated Sheathing plywood and 5 lumber bottom deckboards. Damage observations provide the following information about any damage incident sustained by the pallet: 1) when the damage incident occurred during testing, as indicated by the test cycle; 2) where the damage occurred in the pallet, which is indicated by part location; 3) The appearance of the damage incident, which is indicated by damage mode; and 4) what was the cost associated with the damage incident, which is indicated by the severity level.

The total damage cost for the pallet after any level of use is calculated using Equation 4.3.

Table 4.5 -- Damages which occurred to an example test pallet of the base pallet design as a function of testing cycle

Pallet ID	Test cycle	Damage part	Damage mode	Damage description			Severity level
				Length	Width	Nails	
Base07	2	BC3	S	8	0	0	3
Base07	4	BE1	S	10	0	0	4
Base07	5	CS	C	8	2.5	0	5
Base07	6	BE1	S	13	0	0	5
Base07	6	BC3	MP	14	1	1	8
Base07	8	BC1	S	6	0	1	3
Base07	9	BE1	S	32	0	1	8
Base07	10	BC1	S	16	0	2	4
Base07	11	PT2	C	13	0	0	5
Base07	15	PT2	JF	0	0	2	2
Base07	15	BE1	MP	22	1	0	8
Base07	20	ES1	C	8	2.5	0	5
Base07	22	ES1	MP	6	3	4	9
Base07	23	PT1	ED	4	0.75	0	4
Base07	25	BC1	S	12	0	1	6
Base07	30	PT1	ED	5	0.75	0	6
Base07	30	PT2	ED	11	0.75	0	4
Base07	30	PT1	VT	10	8	0	6
Base07	30	CS	C	8.5	2.5	0	5
Base07	30	BE1	MP	24	1	1	8
Base07	30	BC1	S	11	0	2	4
Base07	30	BC3	MP	11	1	3	8

Note:

BC1, BC2, BC3 = three bottom center boards
CS = Center stringer
ES1, ES2 = two edge stringers
PT1, PT2, PT3, PT4 = four sides of top panel deck
S = split, C = crack, MP = missing part, JF = joint failure

$$C_t = \sum_{i=1}^{N} ab^{S_i} \quad [4.3]$$

Where:

C_t	=	total damage costs of a pallet
N	=	total number of damaged parts
S_i	=	damage severity of i^{th} damaged part
a, b	=	regression coefficients from Equation 4.2

It is common that there are several damage incidents for one component (Table 4.5). For example, one of the bottom end boards denoted by BE1 sustained 5 damage incidents tested after 30 cycles. One damage of the severity 8 occurred after 15 cycles. According to the repair criteria, BE1 should have been replaced after 15 cycles and the costs for such repair is assigned for the BE1. Thus, more damages sustained by the BE1 following 15 cycles do not contribute any cost to the component since no repair was actually performed in this test. That is why the S_i in Equation 4.3 is the damage severity of i^{th} damaged part instead of damage incident. However, the damage is recorded by damage incident. In order to overcome the problem, the adjusted severity level of i^{th} component should be calculated. In order to simplify the calculation, the total damage costs for each individual pallet is calculated using Equation 4.4. That is the total damage costs for a pallet after any cycle of use is the product of the total number of damaged components and the average costs of the damaged components.

$$C_{t,i} = (F_i)(C_i) \qquad [4.4]$$

Where:

C_{ti} = total damage cost of i^{th} pallet

F_i = number of damaged components of i^{th} pallet

C_i = average damage costs of i^{th} pallet

4.3.1 Number of Damaged Components, F

To calculate the total cost of damage to a pallet, it is necessary to calculate the total number of damaged components and combined severity from the test data. The number of damaged components is counted after each test cycle. The total number of damaged components is determined in the following fashion.

1) damages in the same component at the same cycle with the same severity level are considered as one.

2) damages in the same component at the same cycle with different severity levels are considered as one with their combined severity.

3) each component may have more than one number of damage incidents after certain cycles. However, only one number of damages is used to represent the damaged component and its severity was the highest one among them.

4) damages at the same components at different cycles with the same severity level are treated as one and at the lowest number of cycles. This treatment also prevented repeated records.

5) the total number of damaged parts is calculated always with a certain number

of cycles.

The total number of damaged parts after different cycles for 25 replicate base pallets is calculated and showed in Table 4.6. The number of damaged components after each test cycle varies. Furthermore, the variance changes at different test cycle. For the base pallet design, the coefficient of variance of the total number of damaged parts was 20.67 percent after 30-cycle testing. This variation was used as the basis for choosing the sample size for other types of pallets tested in this study. The average number of damaged parts of the base pallets is 7.5 with sample variance of 1.23 after 30 cycles. With 85 % confident interval and significant level of 0.10, a minimum sample size of 5 is needed for other pallet designs. Based on the 5 sample sizes, the average total number of damaged parts of each pallet design represents the expected mean with 85 percent confidence. The average total number of damaged components of a pallet as calculated in this study depends on the total number of components used to fabricate the pallet. The number of components of a pallet is different for different pallet design. For example, panel deck pallets have less components than lumber deck pallets, and block pallets have more than stringer pallets. Therefore, the average total number of damaged components alone cannot be used as a reliable indicator of a pallet durability between these different pallet designs. However, the average total number of damaged parts can be used as an indicator of a pallet's resistance to damage whenever the pallets have same or similar components.

The average total number of damaged parts within a pallet design is used as the expected total number of damaged parts. The expected number of damaged part, F is calculated according to Equation 4.5. The expected total number of damaged parts for all pallet designs by cycle are found in Table 4.7. The average number of damaged parts in Table 4.7 represents the cumulative number of damaged parts after preceding cycles. Figure 4.7 is a plot of number of damaged parts as a function of test cycle for 6 different pallet designs. It should be noted that no repair was performed to any damaged part during the test. If repair have been conducted, the average total number of damaged parts will increase.

$$F = \frac{\sum_{i=1}^{N} (F_i)}{N} \qquad [4.5]$$

Where:

F = expected number of damage parts of a pallet design
N = the number of sample size of the pallet design
F_i = the number of damaged parts of i^{th} pallet

4.3.2 The Average Damage Costs

The average number of damaged parts can be used as a measure of the resistance to damage for those pallets which differed only in the properties of the materials used. However, the number of damaged parts cannot be used to indicate the pallet durability for all different pallet construction characteristics. This is because the different pallet designs contain different numbers of components and different repair costs are associated

Table 4.6 – The total number of damaged parts and average damage costs after each cycle for base pallets tested in the VPI FasTrack

Pallet ID		Cycles tested						
		3	5	10	15	20	25	30
B01	F1[1]	0.00	0.00	1.00	3.00	4.00	4.00	5.00
	C1[2]	0.00	0.00	0.28	0.22	0.30	0.21	0.40
B02	F2	1.00	3.00	4.00	4.00	5.00	6.00	8.00
	C2	0.95	0.70	0.56	0.56	0.46	0.43	0.37
B03	F3	1.00	3.00	6.00	7.00	8.00	8.00	8.00
	C3	0.08	0.10	0.19	0.19	0.21	0.46	0.37
B04	F4	0.00	1.00	2.00	7.00	8.00	8.00	8.00
	C4	0.00	0.12	0.23	0.21	0.35	0.35	0.39
B05	F5	4.00	4.00	5.00	5.00	7.00	7.00	9.00
	C5	0.24	0.24	0.44	0.44	0.47	0.70	0.70
B06	F6	2.00	3.00	3.00	6.00	6.00	7.00	7.00
	C6	0.14	0.15	0.33	0.48	0.51	0.47	0.82
B07	F7	1.00	3.00	4.00	5.00	6.00	7.00	7.00
	C7	0.12	0.20	0.59	0.53	0.49	0.61	0.64
B08	F8	2.00	3.00	3.00	4.00	8.00	9.00	9.00
	C8	0.14	0.15	0.15	0.40	0.38	0.36	0.51
B09	F9	1.00	1.00	4.00	6.00	8.00	8.00	8.00
	C9	0.08	0.49	0.22	0.44	0.52	0.52	0.52
B10	F10	2.00	2.00	4.00	5.00	6.00	6.00	7.00
	C10	0.14	0.52	0.42	0.71	0.61	0.61	0.67
B11	F11	0.00	1.00	3.00	3.00	7.00	7.00	9.00
	C11	0.00	0.19	0.50	0.50	0.31	0.31	0.35
B12	F12	4.00	4.00	4.00	5.00	6.00	8.00	8.00
	C12	0.64	0.64	0.64	0.59	0.79	0.74	0.74
B13	F13	2.00	3.00	6.00	7.00	8.00	8.00	11.00
	C13	0.09	0.09	0.35	0.32	0.50	0.50	0.52

Table 4.6 continued

B14	F14	3.00	5.00	7.00	7.00	7.00	7.00	7.00
	C14	0.09	0.37	0.35	0.35	0.35	0.46	0.57
B15	F15	1.00	1.00	1.00	3.00	6.00	6.00	6.00
	C15	0.12	0.19	0.19	1.10	0.87	0.98	0.98
B16	F16	1.00	3.00	5.00	7.00	7.00	7.00	7.00
	C16	0.28	0.59	0.56	0.65	0.65	0.65	0.67
B17	F17	1.00	2.00	4.00	4.00	5.00	6.00	7.00
	C17	0.12	0.12	0.20	0.64	0.55	0.77	0.64
B18	F18	1.00	2.00	5.00	6.00	6.00	6.00	6.00
	C18	1.42	0.75	0.56	0.56	0.78	0.77	0.77
B19	F19	0.00	0.00	5.00	5.00	6.00	6.00	6.00
	C19	0.00	0.00	0.35	0.37	0.56	0.67	0.67
B20	F20	0.00	0.00	3.00	3.00	3.00	4.00	6.00
	C20	0.00	0.00	0.63	0.63	0.63	0.54	0.74
B21	F21	2.00	2.00	2.00	5.00	5.00	6.00	6.00
	C21	0.16	0.16	0.16	0.45	0.65	0.63	0.63
B22	F22	0.00	0.00	3.00	4.00	8.00	8.00	8.00
	C22	0.00	0.00	0.15	0.18	0.23	0.27	0.27
B23	F23	1.00	1.00	2.00	4.00	5.00	5.00	5.00
	C23	0.124	0.124	0.202	0.23	0.32	0.42	0.65
B24	F24	0.00	2.00	3.00	5.00	6.00	8.00	11.00
	C24	0.00	0.52	0.41	0.47	0.41	0.54	0.66
B25	F25	1.00	1.00	2.00	3.00	3.00	6.0	7.0
	C25	0.12	0.12	0.54	0.95	0.95	0.57	0.62
Base	F^3	1.24	2.00	3.68	5.32	6.16	6.76	7.36
	C	0.20	0.24	0.37	0.50	0.52	0.54	0.60

Note: 1 -- the number of damaged parts for a pallet
2 -- the average cost for the pallet
3 -- the expected number of damaged parts and average damage cost for these pallets. The coefficient of variance of F and C is 20.65% and 27.9%, respectively

Table 4.7 -- Total average number of damaged components by cycle for all pallet designs tested [1]

Pallet design	Cycles tested						
	3	5	10	15	20	25	30
Base design	1.24	2.00	3.68	5.32	6.16	6.76	7.44
Design 1	1.60	2.20	3.80	5.00	5.80	7.40	8.40
Design 3	2.17	2.67	4.33	5.67	6.67	7.83	8.67
Design 2	3.20	4.00	5.00	5.60	5.60	6.00	6.20
Design 4	0.60	1.00	2.60	3.60	4.20	4.60	5.40
Design 8	0.20	1.00	2.80	4.20	5.00	6.40	7.00
Design 10	0.00	0.17	0.67	0.83	1.16	1.83	2.00
Design 13	0.20	0.80	2.20	3.60	4.20	4.80	5.40
Design 7	0.20	0.80	1.80	2.60	4.20	5.00	6.40
Design 11	0.80	1.60	3.20	3.40	4.40	5.60	6.40
Design 15	0.40	0.60	1.60	2.30	3.50	4.30	6.00
Design 6	0.20	0.60	3.40	4.20			
Design 9	0.00	0.00	0.40	1.20	1.80	3.00	3.80
Design 12	0.60	0.80	3.00				

Note:

1 -- the base pallet design included 25 replicates and others 5 replicates. Coefficient of variation of damaged parts within pallet design is typically between 20% -- 30%

with these components.

The average cost of an individual pallet after each cycle was calculated using Equation 4.3, divided by the total number of damaged components. The severity, S_i, in Equation 4.3 is the combined severity of all the damages to a component. Like the total number of damaged components, the average damage cost varies within pallets of the same design. The expected average damage costs for a particular type of pallet is calculated using Equation 4.6. The damage costs of the base pallet design are found in Table 4.6.

$$C = \frac{\sum_{i=1}^{N} (C_i)}{N} \qquad [4.6]$$

Where:

C = Expected average cost of a pallet design
C_i = Average damage costs of i^{th} pallet of the same design
N = Number of pallets of the design

Figure 4.8 is a plot of the average damage cost as a function of test cycle for 6 different pallet designs. It is interesting to note that after 5 cycles the average damage costs are independent of the number of test cycles. This implies that the average damage cost after 5 cycles is dependent only on the pallet design. This result confirms the assumption of Wallin (1984). It is noted that pallet design with higher number of damaged parts does not mean it has the higher average damage cost.

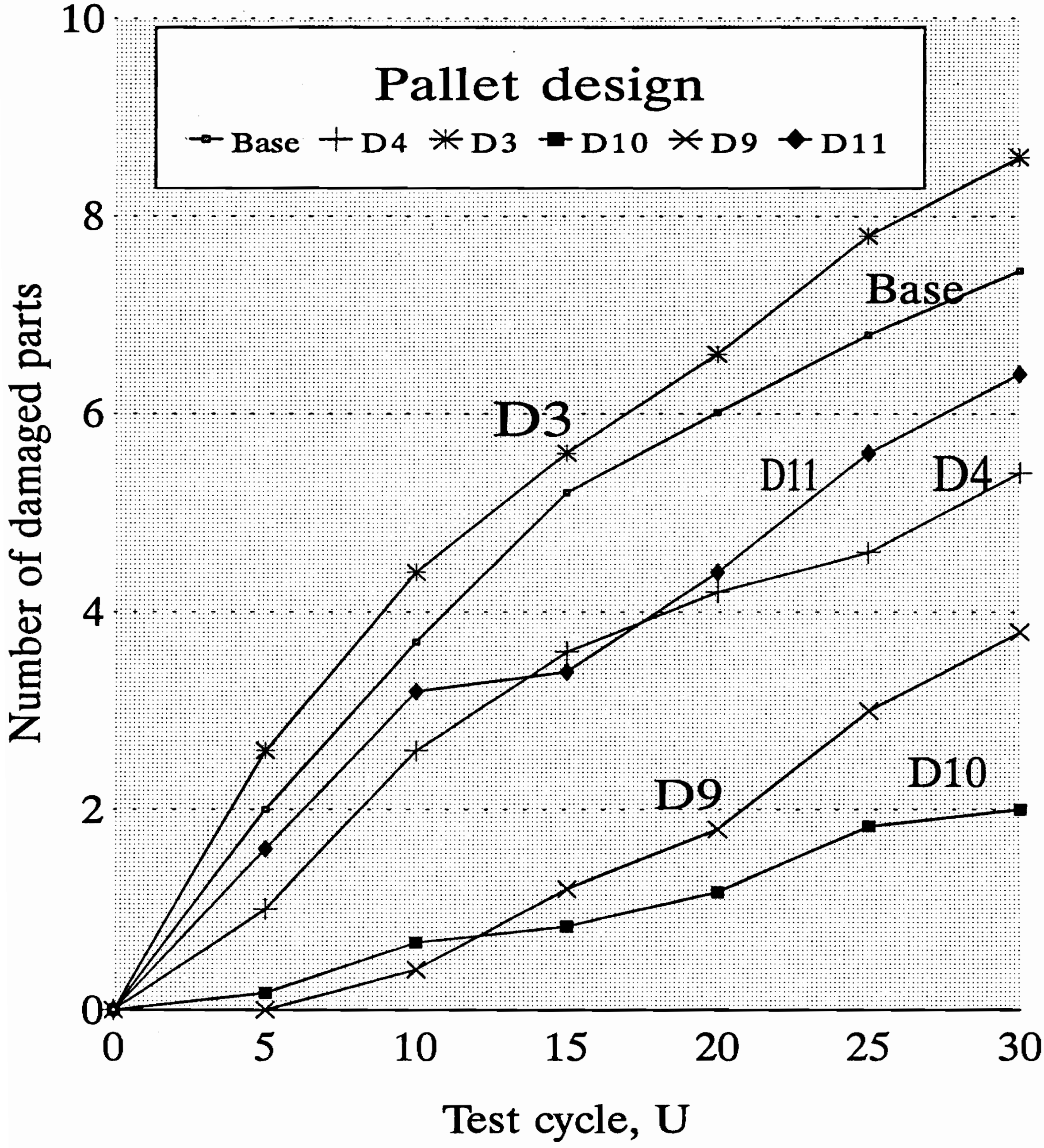


Figure 4.7 -- The average total number of damaged parts as a function of test cycle for 6 different pallet design

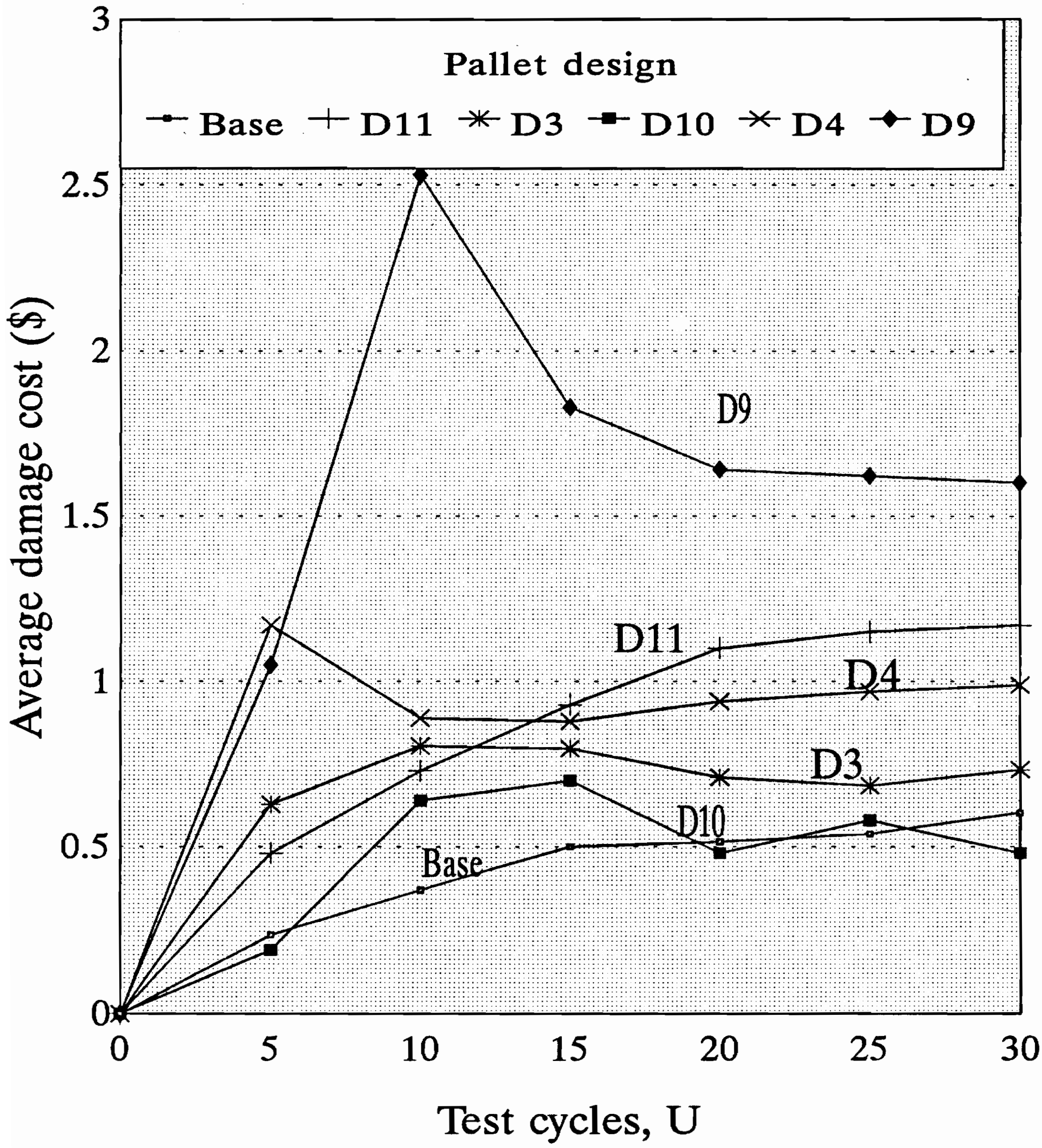


Figure 4.8 -- The average damage cost as a function of test cycle for 6 different pallet designs

5.0 MODEL DEVELOPMENT

5.1 Modeling the Economics of Pallet Use

Since no repair was conducted in the handling test, the total damage costs obtained from the test do not represent the real relationship between the total damage costs and cycles if the repair would have been conducted in the test. According to the description of damage severity and the criteria of repair, any damaged component with a damage severity level higher than 6 should be repaired. Unfortunately, no repair was performed during the test. Hence, the maximum number of damaged parts is always less than the total number of components used to assembly the pallet, which is not necessarily true in reality.

In reality, repair is conducted whenever the severity level of the damaged component exceeds the level which requires repair. The repaired components may then be damaged again during continued pallet use. Therefore, it is possible that the total number of damaged components for any pallet can exceed the total number of components used in the assembly of the pallet. In order to reflect the actual economics of use of pallet, the total damage cost from this study was adjusted to account for pallet repairs.

5.1.1 Data Conversion

The purpose of this analysis is to determine: 1) how many damaged parts require repair at each 5-cycle increment; and 2) the distribution of the life expectancy of pallet parts in terms of cycles (i.e. the number of pallet parts which have the same life expectancy). Table 5.1 contains the total number of damaged parts as well as the number of damaged parts which require repair in all the 25 base pallets after each five-cycle handling increment. For example, after 5 cycles, the total number of damaged parts are 50. Eleven of these damaged parts require repair. After 10 cycles, the total damages parts are 92 and 27 required repair. It should be noted that the 27 damaged parts after 10 cycles include the 11 damaged parts after 5 cycles. If the 11 damaged parts had been repaired after 5 cycles, the total number of damaged parts after 10 cycles may have increased. The problem is how different would it be. In order to address this issue, the following assumptions are made.

1) Any damaged component returns its original state after it is replaced or repaired.

2) A repaired component does not affect other components in the pallet.

3) The performance of a repaired component is independent of the conditions of other components in the pallet.

4) The damage costs of the repaired component will be the same as the original one if the repaired one is damaged again.

From the assumption 1, 2, and 3, a repaired component is assumed to have the same life expectancy as the original one. For example, if the original one has the life expectancy of 5 cycles, the replaced one would also have the life expectancy of 5 cycles. Furthermore, the total damage costs can be adjusted by only adjusting the total number of damaged components since the average damage cost is assumed the same. The number of adjusted damaged components are determined from the distribution of the life expectancy of the pallet components, shown in Table 5.2 for the base pallets. The distribution of the life expectancy of pallet components is the number of components at each 5-cycle increment. Among the 117 damaged parts after 30 cycles, 11 required repair after 5 cycles, 22 after 10 cycles, 23 after 20 cycles, 18 after 25 cycles, and 28 after 30 cycles. If these components would have been repaired, the total number of damaged components, after 10 cycles, would be the initial number of damaged parts plus 11 survived another 5 cycles. The adjusted total damaged components after 15 cycles would be the initial 133 damaged parts plus the sum of 2 times 11 and 16 since the 16 damaged parts only have 10 cycles of life expectancy (see Table 5.2). The total adjusted number of damaged parts is then 171. The same method is applied to adjust the total number of damaged parts at each 5-cycle increment. The adjusted total number of damaged parts are listed in Table 5.2 for the base pallet design. The factors shown in Table 5.2 for the base pallet are used to adjust the total number of damaged components in the other pallet design (D1-D15) in order to be consistent and because the base pallet represents the largest replicate. Table 5.3 is the average adjusted cumulative damage cost by test cycle for all pallet designs tested. Figure 5.1 is a plot of adjusted average total damage cost as a function of test cycle for 6 different pallet designs.

Table 5.1 -- Total number of damaged parts and number of damaged parts which require repair by test cycle for the base pallet design

Cycle	Total number of damaged parts	Total number of parts require repair	Number of parts with the life expectancy [1]	Percentage (%) of damages need repair [2]
5	50	11	11	22.00
10	92	27	16	29.35
15	133	49	22	36.84
20	154	71	23	46.10
25	169	89	18	52.66
30	186	117	28	62.90

Note:

1 -- the life expectancy of pallet part is corespondent to the cycle

2 -- It represents the percent of the total number of damaged parts require repair

Table 5.2 -- The adjustment of the total number of damaged parts considering the repair for the base pallet design

Cycle	Initial number of damages	The number of damaged parts repaired [1]						Adjusted number of damages[2]	Adjustment factor[3]
		5 cycle life	10 cycle life	15 cycle life	20 cycle life	25 cycle life	30 cycle life		
5	50	0	0	0	0	0	0	50	1.00
10	92	1X11	0	0	0	0	0	103	1.120
15	133	2X11	1X16	0	0	0	0	171	1.286
20	154	3X11	2X16	1X22	0	0	0	241	1.565
25	169	4X11	3X16	2X22	1X23	0	0	328	1.941
30	186	5X11	4X16	3X22	2X23	1X18	0	435	2.339

Note:

1 -- the number of damaged parts repaired is based on the life expectancy of the parts
2 -- adjusted number of damages equals the initial number of damages plus the sum of the number of damaged parts repaired
3 -- adjustment factors multiplied by the initial number of damages equals the adjusted number of damages

Table 5.3 – The average adjusted cumulative total damage cost by cycle for all pallet designs tested

Pallet design	Cycles tested					
	5	10	15	20	25	30
Base design	0.48 (35.3)	1.52 (23.6)	3.42 (18.5)	4.96 (19.7)	7.06 (20.2)	10.09 (20.7)
Design 1	1.21 (50.1)	2.45 (25.4)	3.44 (17.4)	5.33 (25.7)	8.55 (11.5)	12.81 (5.9)
Design 3	1.58 (34.4)	4.22 (31.8)	6.07 (26.9)	7.69 (17.9)	10.32 (14.1)	14.61 (13.1)
Design 2	2.73 (30.6)	4.62 (0.0)	6.26 (7.7)	8.23 (7.7)	11.14 (0.0)	13.79 (7.0)
Design 4	1.40 (37.3)	2.65 (16.1)	4.21 (22.4)	6.53 (11.7)	8.69 (17.6)	12.32 (15.8)
Design 8	0.54 (37.3)	2.53 (24.1)	4.10 (10.2)	6.51 (16.1)	8.71 (7.8)	11.05 (17.5)
Design 10	0.04 (186.3)	0.67 (77.4)	1.05 (40.4)	1.07 (36.4)	2.44 (21.8)	2.24 (22.8)
Design 13	0.63 (9.3)	1.63 (19.4)	2.55 (13.9)	4.48 (22.2)	5.89 (11.4)	8.96 (15.8)
Design 7	0.46 (96.5)	1.77 (25.5)	2.82 (20.2)	5.08 (11.8)	8.55 (9.8)	13.62 (7.8)
Desing 11	0.54 (67.53)	2.50 (23.5)	3.67 (23.7)	7.04 (17.9)	12.28 (15.7)	17.81 (13.4)
Desing 15	0.21 (109.1)	1.63 (36.4)	2.05 (47.8)	3.98 (47.8)	5.98 (14.1)	8.65 (7.0)
Design 6	0.37 (143.9)	7.03 (29.9)	8.39 (28.9)	11.51 (10.2)	14.27 (10.2)	17.20 (10.2)
Design 9	0.00 (0.0)	0.80 (156.5)	2.93 (34.9)	4.51 (24.6)	9.44 (23.6)	14.04 (22.1)
Desing 12	0.80 (92.4)	5.26 (23.6)	6.04 (23.6)	7.34 (23.6)	9.11 (23.6)	10.98 (23.6)

Note:

1 – Values in the parentheses are coefficients of variations

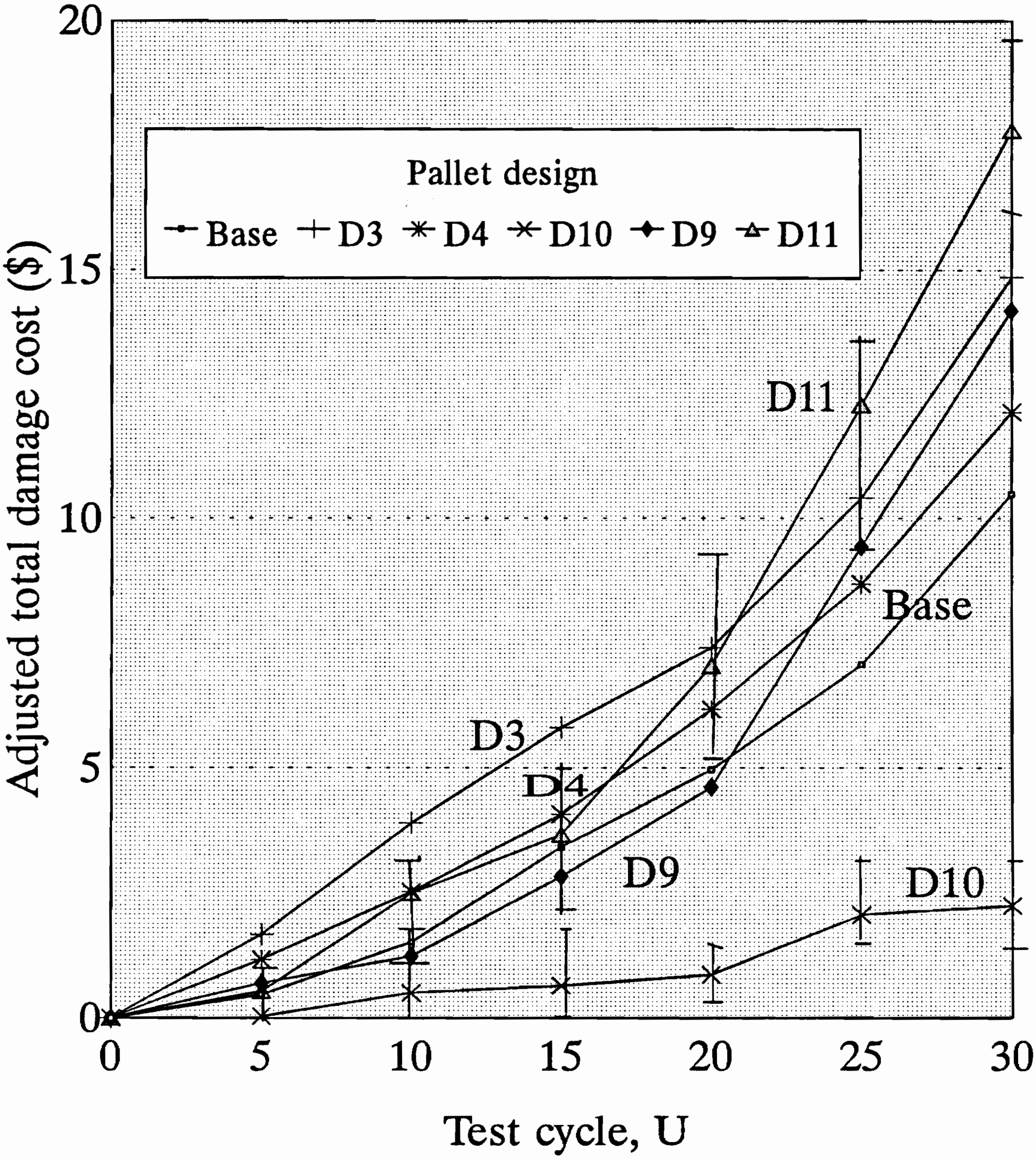


Figure 5.1 -- The average adjusted total damage cost as a function of test cycle for 6 different pallet designs (the brackets for design D10 and D11 represent the range in total damage cost among the five pallets)

5.1.2 Curve Fitting

In order to predict the average total damage cost after any cycle of uses, an empirical relationship between the average total damage costs and test cycles is derived using regression analysis. The following criteria was used for deriving this relationship.

1) The equation must be relatively simple so as to be useful for prediction purpose.
2) It must describe accurately the experimental relationship.
3) It must be differentiable.
4) It must have a degree of predictability based on the pallet structural designs.
5) It must be continuous within the test range and must pass through the origin. That is before use the average total damage cost is zero.

The average total damage costs from base pallets are plotted in a natural form shown in Figure 5.2. From the plot, it is evident that the average total damage cost is an exponential function of the test cycle. Therefore, the mathematical form selected is:

$$C_t = a^U - 1 \qquad [5.1]$$

Where:

C_t = average total damage cost
U = the number of use, cycle
a = coefficient

The equation is fit to the data by TBLCURVE which is a computer software (Janel Scientific, 1990). The result of regression analysis indicates that Equation 5.1 provides a good fit to the data of base pallet design with $R^2 = 0.979$ and a regression coefficient a = 1.086. Figure 5.2 graphically presents the goodness of the fit. The same format is fit to all pallet designs tested in this study. Due to their large space requirements the test plots are omitted from the text. However, the estimated parameters and quality of fit for all the pallets are presented in Table 5.4. It is concluded that Equation 5.1 is a suitable model for describing the relationship between the average total damage cost and the number of uses for panel deck pallets. It is noted that the variance of the total damage cost of a pallet design varies at different cycles. After 10 cycles, the coefficient of variation of total damage costs for all pallet designs tested in this study is 7 to 30 percent. The higher the cycles, the lower the variance. The results of ANOVA analysis reject the null hypothesis that the average damage costs of all pallet designs are the same. Therefore, the regression coefficient "a" in Equation 5.1 is unique for different pallet designs. It is noted that the average total damage cost of many of the designs was not significantly different. However, it is valid to use the average total damage costs to determine the relationship between the total damage cost and the number of use. Based on the 30-cycle test in the VPI "FasTrack", the pallet design related property "a" can be determined using least squares. Figure 5.3 is the plots of predicted average total damage costs for six typical panel deck pallet designs.

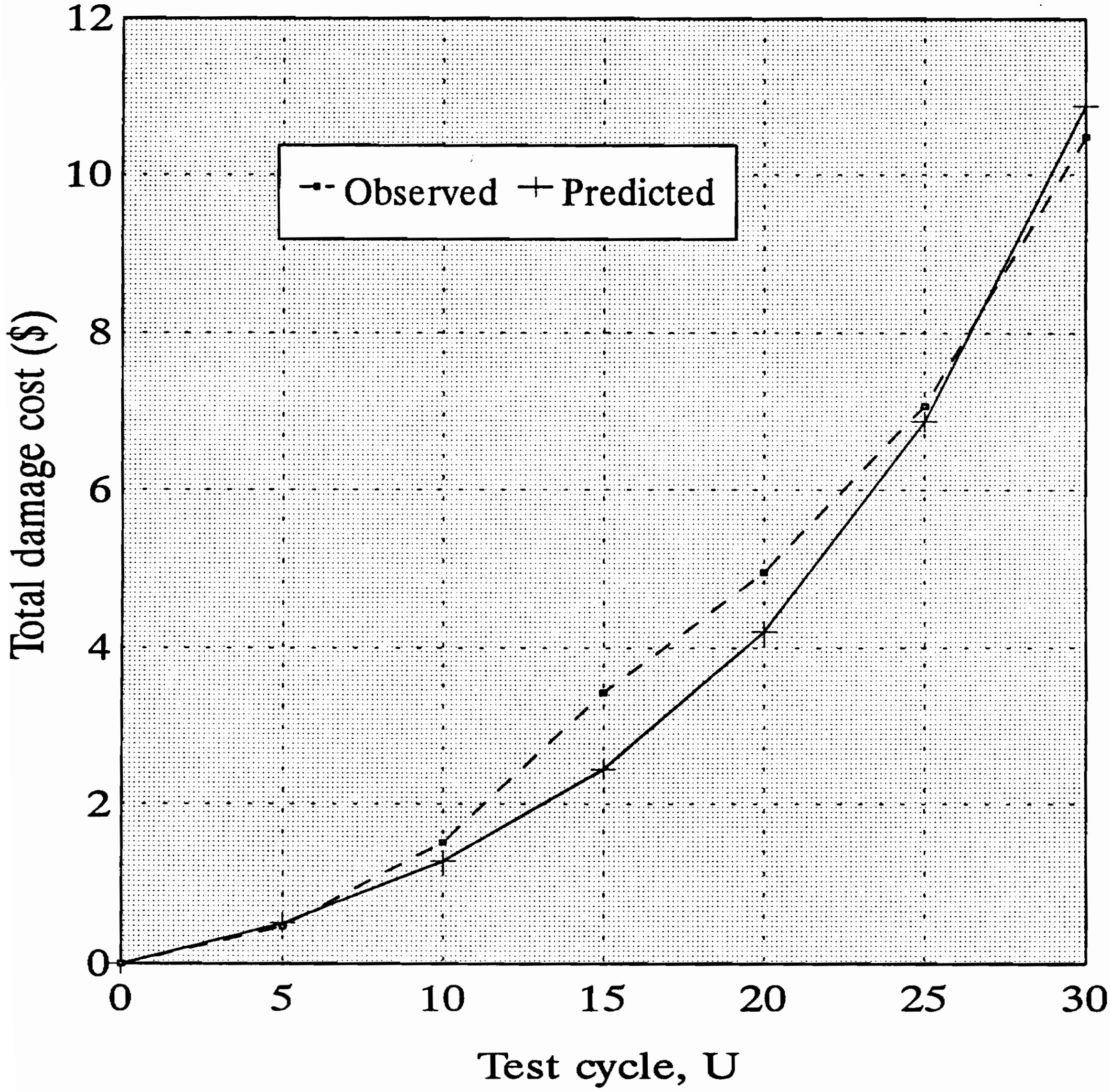


Figure 5.2 -- The observed total damage cost comparing with the predicted total damage as a function of test cycle for base pallet design

Table 5.4 -- Results of regression analysis of adjusted pallet total damage cost as a function of test cycle[1]

Pallet Design	Regression coefficient	Correlation coefficient	90% confident limits	
			low	up
base	1.0860	0.979	1.0833	1.0888
D1	1.0923	0.977	1.0894	1.0951
D3	1.0992	0.860	1.0927	1.1057
D2	1.0984	0.620	1.0889	1.1080
D4	1.0914	0.950	1.0872	1.0955
D8	1.0900	0.917	1.0846	1.0954
D10	1.0405	0.926	1.0366	1.0443
D13	1.0818	0.972	1.0787	1.0848
D7	1.0797	0.993	1.0782	1.0813
D11	1.1044	0.974	1.1011	1.1076
D15	1.0908	0.999	1.0903	1.0914
D6	1.1738	0.892	1.1353	1.1807
D9	1.0952	0.989	1.0848	1.0896
D12	1.1471	0.756	1.1049	1.1601

Note:

1 -- equation, $C_t = a^U - 1$, fit to all the pallet designs

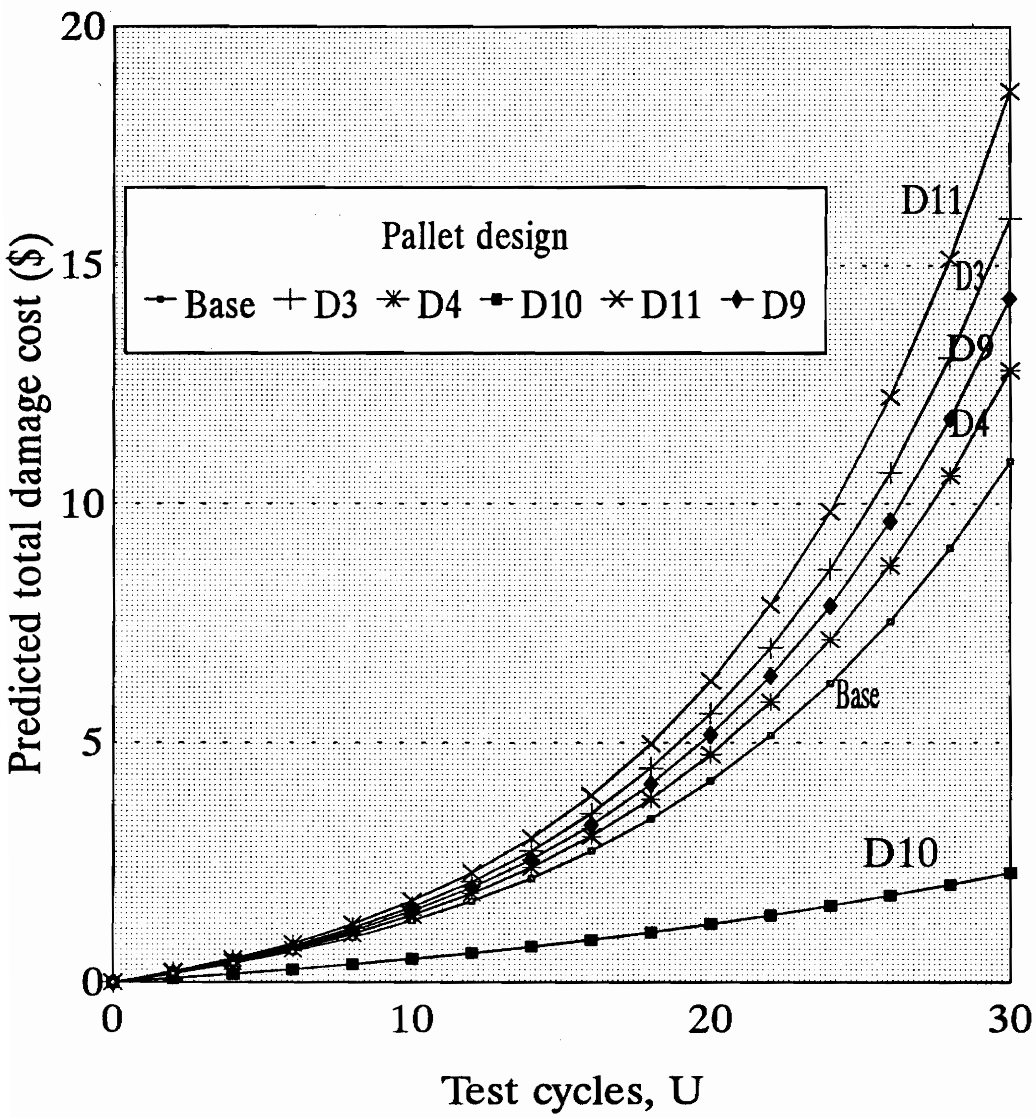


Figure 5.3 -- The predicted average total damage cost as a function of test cycle for 6 different pallet designs tested in this study

5.1.3 The Economic Life of Pallets Tested in this Study

Given an initial price, P, for a pallet, it is possible to predict the durability based on the total damage cost, C_t as a function of the number of cycle, U, described by Equation 5.1. These include the average cost per cycle and the number of cycles at which the cost per cycle is a minimum or the economic life of the pallet. The average cost per cycle of the pallet is computed by Equation 5.2.

$$C_a = \frac{(P + a^U - 1)}{U} \qquad [5.2]$$

Where:

P = purchase price of the pallet
U = number of cycles in the VPI FasTrack system
a = the coefficient of total damage cost
C_a = average cost per cycle

Differentiating Equation 5.2 and equating to zero, a transformation of this relationship is found in Equation 5.3.

$$f(U) = (a^U)\ (Lna^U) - a^U - (P-1) \qquad [5.3]$$

Equation 5.3 must be solved by a process of successive approximation. The solution is given by Equation 5.4.

$$U_{i+1} = U_i - \frac{f(U_i)}{f'(U_i)} \qquad [5.4]$$

This equation is solved iteratively with U_{i+1} replacing U_i until the value of U converges to within a specified tolerance. In this case, if $U_{i+1}-U_i < 0.01$, the U_{i+1} is considered as the solution of Equation 5.3. The f'(U) is calculated by Equation 5.5.

$$f'(U) = a^U (Lna)(Lna^U) \qquad [5.5]$$

The economic life for all the pallet designs calculated using the above described method is shown in Table 5.5. The purchase prices for these pallets are roughly estimated.

5.5 -- The calculated economic life for all the pallet designs tested in this study

Pallet Design	Estimated price ($) [1]	Correlation coefficient	Economic Life (cycle)[2]	Solution Tolerance
Base	20.00	1.0860	32.32	0.026
D1	20.00	1.0923	30.21	0.004
D3	20.00	1.0992	28.20	0.004
D2	22.00	1.0984	27.54	0.002
D4	22.00	1.0914	29.55	0.004
D8	25.00	1.0900	31.00	0.003
D10	30.00	1.0405	70.20	0.001
D13	25.00	1.0818	33.50	0.008
D7	20.00	1.0797	32.90	0.002
D11	20.00	1.1044	25.40	0.003
D15	20.00	1.0908	29.03	0.015
D6	18.00	1.1738	15.33	0.002
D9	18.00	1.0952	27.02	0.001
D12	18.00	1.1471	19.90	0.002

Note:

1 -- the purchase prices of these pallets are roughly estimated.

2 -- the economic life is a theoretical solution based on the solution tolerance. In practice, the economic life is rounded to an integer

5.1.4 Calibration of the VPI "FasTrack" Material Handling System

The economic model (Equation 5.3) used to predict the economic life of panel deck pallets is based on the relationship between the total damage cost and the test cycle (Equation 5.1), which is an empirical relationship derived from testing pallets in the VPI "FasTrack". The objective of this research was to develop a method of predicting the durability of panel deck pallets in a commercial handling system. Therefore, a calibration of cycle in the VPI "FasTrack" with commercial handling cycles is necessary.

This calibration can be performed using two methods. One is to compare the number of physical handlings a pallet experienced in the VPI FasTrack with those in commercial handling systems. The other is to test a pallet of known durability in a commercial system in the VPI "FasTrack".

5.1.4.1 Calibration Based on the Number of Physical Handlings

In this method, it is assumed that the effect of a handling on pallet damage is independent to material handling systems. That is the same number of handlings under any material handling system will cause the same amount of damages to pallets. As has been discussed, each test cycle in the VPI "FasTrack" system contains about 12 handlings. Thus, 30 cycles include about 360 handlings. The handlings can be easily related to the number of commercial trips or the number of years used in the field if the number of handlings per commercial trip is known. The number of times a pallet is handled per year or per trip differs between different material handling system.

Therefore, the "FasTrack" test cycle is calibrated against the following three handling systems which have been studied from the previous studies.

1. According to a study by Wallin and Strobel (1973), pallets used in the 16 different handling environments are exposed in an average of 20 trips per year at an average of 5 handlings per trip. Therefore, the 30 cycles which are 360 handlings tested in the VPI "FasTrack" simulate about 72 trips or 3.6 years of use in the PEP described handling systems. That is that each cycle in the VPI is equivalent to 2.4 commercial trips.

2. According to Pennington and Carney (1972), the average number of handlings per year for the plywood pallets are 200. Hence, the 30-cycle test simulates 1.8 years of use in those specified handling systems.

3. According to Proctor & Gamble Co. (1989), pallets used in the U.S. dry grocery industries experienced about 6 trips per year and each trip receive about 12 handlings. Therefore, the 30-cycle test in the VPI FasTrack simulate 5 years of use for the typical dry grocery sectors in the U.S. That is to say that one cycle in the VPI equals to one commercial trip in the dry grocery industry.

From the above analysis, it is evident that the commercial trip is a misleading term to represent the number of pallet uses since each trip contains different number of handlings depending on particular handling system. Therefore, the number of handlings should be used to represent the number of pallet uses.

5.1.4.2 Calibration Based on Amortized Pallet Life

The calibration based on the physical handling is simple, but depends on the specific handling systems. Durability based on amortization is not only dependent to the number of handlings, but also on the repair criteria and costs. Different repair costs result in different damage costs which affect the ultimate decision of whether to repair or replace a pallet.

In order to calibrate the economic life, 30 replications of Canadian Pallet Council (CPC) pallets were selected and tested in the VPI "FasTrack" system. This is a partial 4-way, 3 notched stringers, lumber deck pallet design. There are two outside stringers, 2-3/4" wide and 3-7/8" high, plus one center stringer that is 1-3/4" wide and 3-7/8" high. The top deck consists of two tightly butted boards, 7/8" thick and 6" wide, on each end of the pallet, and four center boards, 7/8" thick and 4" wide. The bottom deck consists of two 6" wide leadboard and three center boards of which is consisted two 4" wide boards spaced by one 6" wide board. Mixed dense hardwoods are used for the pallets. The detailed specification of the CPC pallet is shown in Table 5.6. The four view schematic diagrams is shown in Figure 5.4. This is a typical pallet design used in grocery industry in Canada and has been used for many years. Experience indicates this pallet is amortized after an average of 7 years of use (CPC, 1987).

The results of the 30 CPC pallets tested in the VPI FasTrack are shown in Table 5.6. The results include the average total number of damaged parts, percentage of the damaged parts requiring repair, average costs of the damaged parts, and the adjusted total damage costs as the function of the test cycle. The plot of adjusted total damage cost as a function of test cycle is shown Figure 5.5. Equation 5.1 is fit to the plot and the regression coefficient is 1.0692 with the range of 1.0672 and 1.0713 at 90% confidence limits. Hence the total damage cost as a function of the test cycle is:

$$C_t = (1.0692)^U - 1 \qquad [5.6]$$

Where:

C_t = total damage cost
U = the test cycle in the VPI "FasTrack"

According to the Canadian Pallet Council, the purchase price of the pallet in 1992 was about $13.00 US. The economic life of the pallet is determined by solving Equation 5.3 in which a is replaced by 1.0692 and P replaced by 13. The resulted economic life of the CPC pallets tested in the VPI "FasTrack" is 33.5 cycles with 0.017 solution tolerance. Based on 7 years of life in the field for the same pallet, it is concluded that the 33.5 cycles simulated 7 years of the field use. That means the 30-cycle test in the VPI FasTrack simulates about 6 years of the field use.

By comparison of these two methods, it implies that pallets tested in the VPI "FasTrack" system may be handled more roughly than in the field. It should be pointed out that more strict repair criteria in the VPI "FasTrack" also contribute to the ability to simulate about 6 years of uses with 360 handlings. One may conclude that the VPI 30 cycle test simulates 5-6 years of use in the dry grocery unit load handling system.

Table 5.6 -- A general description of CPC pallet design

Pallet length: 48"
Pallet width: 40"

Stringer:

End stringers: Height: 3-7/8" Width: 2-3/4" Length 48"
Center stringer: Height: 3-7/8" Width: 1-3/4" Length 48"

Top Deck:

No. of 6's: 4 Thickness: 7/8" Width: 5-7/8" Length 40"
No. of 4's: 4 Thickness: 7/8" Width: 3=7/8" Length 40"
No. of nails per joint at 6's boards: 4
No. of nails per joint at 4's boards: 2

Bottom Deck:

No. of 6's: 3 Thickness: 7/8" Width: 5-7/8" Length 40"
No. of 4's: 2 Thickness: 7/8" Width: 3-7/8" length 40"
No. of nails per joint at 6's boards: 4
No. of nails per joint at 4's boards: 2

Notch: Location: 6" from end
Length: 9"
Depth: 1-1/2"

Chamfers: The bottom lead boards are chamfered on both upper sides and the bottom inner lead boards are chamfered on the upper exposed side

Shook Species: Mixed hardwood

Nails:
Length: 2.25 Wire diameter: 0.120" Thread diameter: 0.130 Head diameter: 0.281 Thread angle: 68° Flutes: 4 MIBANT: 15°

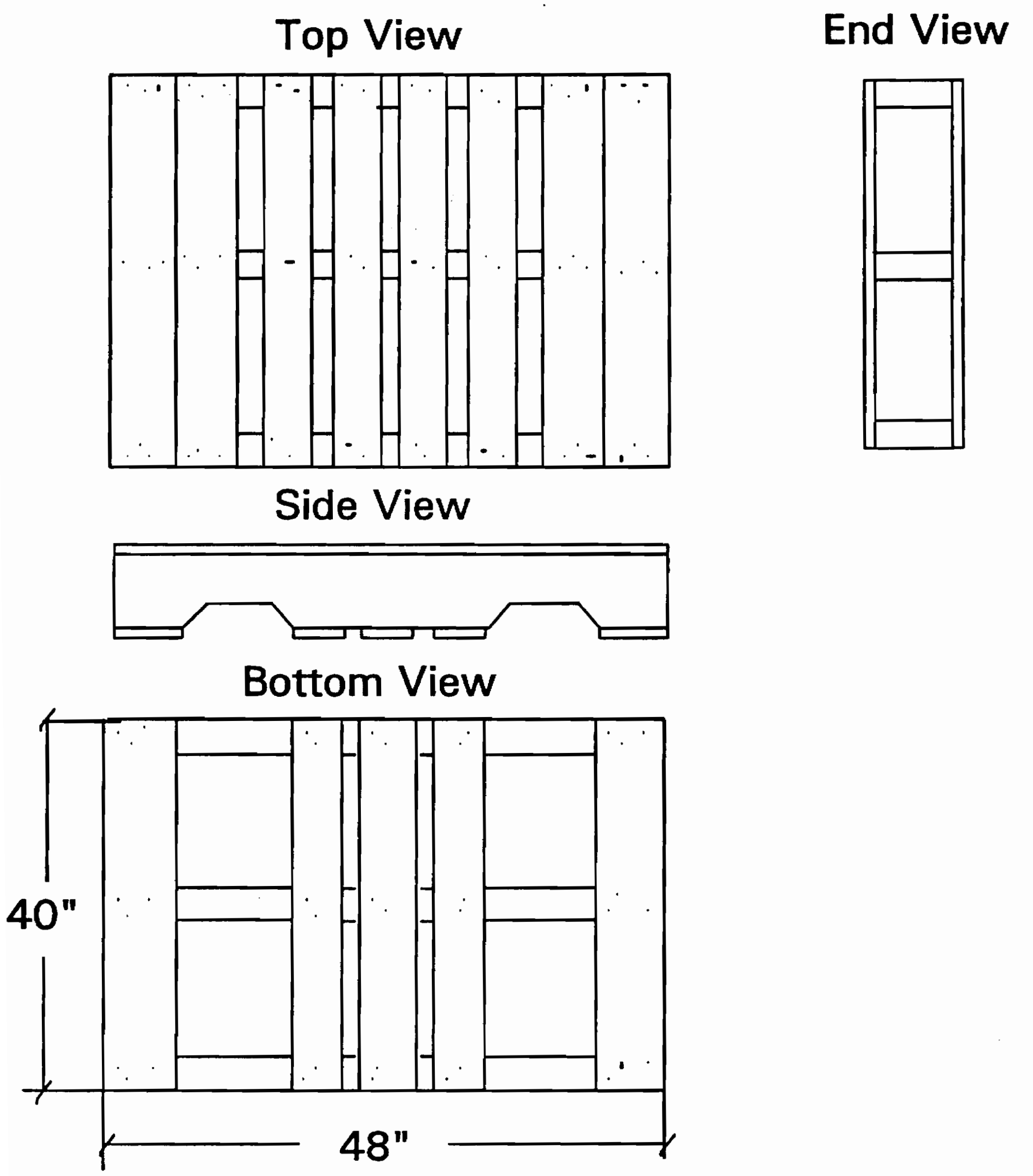


Figure 5.4 -- Schematic diagram of CPC pallet design

Table 5.7 -- Results of VPI FasTrack handling test for CPC pallet design

Test cycle	Average total number of damaged parts [1]	Adjusted total number of damaged parts [2]	Average damage cost ($)	Total damage cost ($)
5	0.767 (0.95)	0.767	0.13	0.10
10	2.833 (0.36)	3.173	0.21	0.68
15	3.833 (0.24)	6.172	0.22	1.35
20	4.500 (0.25)	10.710	0.25	2.65
25	5.233 (0.22)	17.322	0.24	4.13
30	6.627 (0.22)	27.998	0.24	6.73

Note:

1 -- values in the parentheses are coefficients of variation
2 -- adjustment is based on the distribution of pallet part's life expectancy

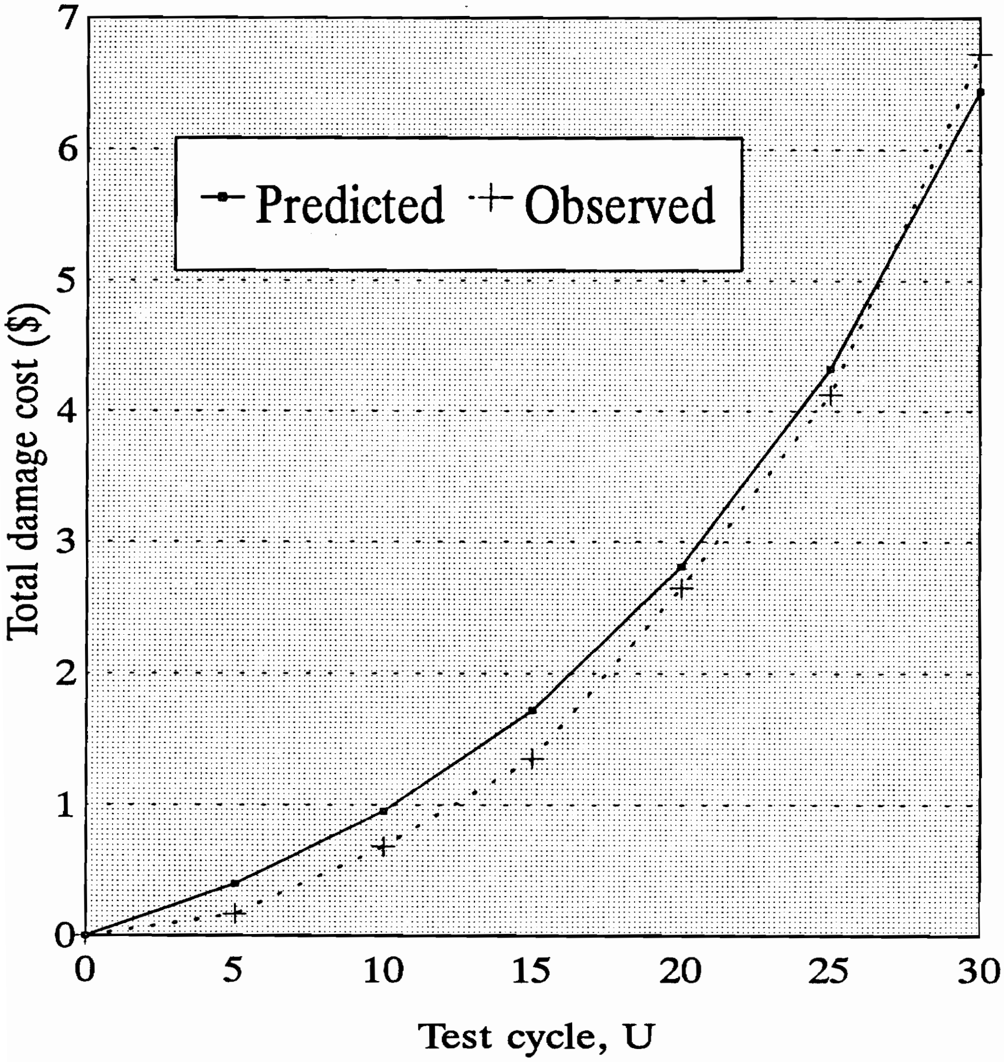


Figure 5.5 -- Plot of predicted and observed total damage cost as a function of test cycle for CPC pallet design

5.2 Relating Pallet Structural Design Characteristics to Structural Durability -- Developing the Structural Design Model

One of the most important objectives of this study is to evaluate how well the estimated coefficients (Table 5.4) of the model of economics of use (Equation 5.1) can be predicted from known pallet structural properties. In this evaluation extensive use is made of multiple regression techniques for relating several independent variables to a dependent response.

Multivariate regression analysis is a statistical tool for evaluating the relationship of one or more independent variables to a single, continuous dependent variable. It is most often used when the independent variable cannot be controlled as it is in this case.

The initial step in multiple regression analysis is the hypothesis of some model of the dependent variable and the independent variables or predictors. The response variable in this study is the estimated model parameters of the total damage cost relationship. The independent variables are the pallet structural properties. As has been discussed, there are many design variables in the pallet construction. It is impossible to use each of them as a predictor. Hence, the independent variables are selected based on the results of this study, previous studies, and the physical understanding of the dependent response (Stern, 1968, 1969, 1976; Osborn, 1985; Kurtenaker, 1973).

5.2.1 Pallet Structural Properties

From previous studies, relationships have been derived which relate pallet structural design to performance, such as the fastener withdrawal resistance, fastener shear resistance, etc. (Wallin, 1984). These relationships have been used to predict the durability of lumber deck pallets (Wallin, 1984), which are discussed in Appendix A. However, some problems should be pointed out here. Firstly, the formulas calculating the properties are restricted to the stringer type, lumber deck pallets. Secondly, there is severe collinearity among the variables. Therefore, the model is very unstable and restricted only the pallets tested in the PEP study.

Pallets tested in this study varied not only in terms of classifications, but also varied in terms of the materials used. The detailed specifications of the pallets tested are found in Appendix C. These designs include a large number of correlated structural design variables. These variables may constitute a set of potential predictors or simply a set of variables needing to be described or interpreted together. Therefore, the variable reduction method is used. That is to use small sets of variables to replace the entire original set. There are several benefits from doing this: 1) to eliminate collinearity 2) to simplify data analysis; 3) to obtain a conceptually meaningful summary of the data. The following summarizes the reduced variables derived from the original set.

5.2.1 Panel Shear Resistance Through the Thickness

All the pallets are fabricated with structural panels as the top deck. Most damage occurring to the panel deck from the handling tests are either edge dent or veneer torn off. Such damage is caused by the impact of forklift or pallet jack. It is believed that the resistance to shear through the thickness of structural panel provides the resistance to these types of damages. Therefore, the shear resistance through the thickness of structural panel is selected as a candidate predictor. The shear resistance through the thickness is calculated using Equation 5.7. Allowable shear through the thickness is the capacity to resist horizontal shear breaking loads when loads are applied or developed on opposite edges of the panel. The allowable shear capacity through the thickness is a design value for a given Performance Rated structural panel, which is in Tables 2.4 and 2.4.1 of the Design Capacities of APA Performance Rated Structural-Use Panels (APA, 1991). The FvTv is determined by panel type, panel grade, and span rating.

$$STT = (f)\,(F_v T_v)\,(T) \qquad [5.7]$$

Where:

STT	=	panel shear strength through the thickness, lbs
F_vT_v	=	allowable shear capacity through thickness, pounds per inch thickness, ibs/inch
T	=	thickness of the panel, inches
f	=	panel type factor, f=1 for plywood and f=0.55 for OSB

In this way, all the variables, such as panel type, grade, thickness, and span rating, related to panels are combined into a single variable. Since any one of the panel related variables causes the change of the shear resistance through the thickness, it is possible to assess each individual panel related variable if the shear through thickness does provide the prediction of pallet durability.

5.2.1.2 Bottom Deck Strength

It has been shown that the resistance of pallet components to damage is a function of the strength of the components. Since different components in pallets are subject different stresses, the strength of pallet components is modeled separately.

The bottom deck strength is defined as the flexure strength spanned across pallet width. Pallet width is defined as the direction perpendicular to the stringer in the stringer pallets, and perpendicular to the strength direction of the structural panel in top deck of block pallets. The bottom deck strength (BDS) is modeled as a composite beam acting over a free span. For simplicity, the BDS is based on an uniformly distributed loading. The bottom deck could be constructed with either lumber deckboards or a structural panel. Hence, the BDS is calculated separately.

For lumber bottom deck pallets, the strength is calculated by Equation 5.8, which is a modification of the beam equation for an uniform load with two end supports. It is assumed that all the bottom deckboards parallel to the 40" direction of the pallets are acting together as a wide, thin beam.

$$BDS = \frac{2.133(b)(h^2)(F)(L)(f_g)}{(L-W(s/b))^2} \qquad [5.8]$$

Where:

BDS	= bottom deck strength for lumber deckboards, lbs
b	= cumulative width of bottom deckboards, inches
h	= thickness of bottom deckboards, inches
L	= length of the deckboard, inches
f_g	= grade factor, $[1-0.08\,(C)^{.75}]$
F	= working stress in bending = 0.3 MOR, psi
C	= average deckboard grade based on PEP grading rules
W(s/b)	= width of edge stringer or corner block, inches

The W(s/b) is the width of a edge stringer for stringer pallets or the width of a corner block for block pallets. It should be noted that the BDS for perimeter base, block pallets is calculated only considering the outer deckboards. Hence, the cumulative width of bottom deckboards, b, in Equation 5.8 is calculated accordingly. The grade factor, fg, is derived by Wallin (1984) to reflect the strength reduction by varying the grade of the deckboards. The grading rules (Appendix D) developed during the PEP study are used.

For unidirectional base, block pallets, the BDS is calculated based on the direction of the bottom deckboard orientation. If they are parallel to the width of the pallet, it is calculated by Equation 5.8. If they are parallel to the length of the pallet, it is assumed to zero.

For panel bottom decks, the bottom deck strength is calculated using Equation 5.9. This represents panel bending strength based on an uniform loading (APA, 1991) with simple span. The allowable bending strength capacity, F_bS, and section modulus, S are in Tables 2.1, 2.1.1, and 2.5 of the Design Capacity of APA Performance Rated Structural-Use Panels (APA, 1991). The allowable bending strength capacity perpendicular to the strength axis of structural panel is used in Equation 5.9. W(s/b) is the width of an edge stringer for stringer pallets or the width of a corner block for block pallets. It is noted that the allowable extreme fiber stress in bending, F_b can be used to replace the (F_bS/S) in Equation 5.9.

$$BDS = \frac{16\,(F_bS/S)\,(L)\,(B)\,(h^2)}{(B-W(s/b))^2} \qquad [5.9]$$

Where:

BDS	=	bottom deck strength for panel bottom deck, lbs
F_bS	=	allowable panel bending strength capacity, units are Ib-In. per foot of panel width.
L	=	Length of panel parallel to span direction, inches
B	=	width of panel perpendicular to span, inches
l	=	free span, l = B-W(s/b), inches
S	=	section modules of structural panel, in.^{3}/ft
h	=	thickness of structural panel, inches

The bottom deck strength represents the properties of the bottom deck materials as well as their orientations. Hence, it is selected as a potential predictor. This variable reflects the effect of bottom deck construction on pallet durability. From Equation 5.8 and 5.9, it is noted that the BDS is calculated by the following pallet construction variables: 1) type of bottom decks (panel or lumber); 2) panel grade and orientation; 3) species, grade, and dimension, and orientation of lumber deckboards. In this way, many structural design variables of bottom decks can be evaluated.

5.2.1.3 Pallet Strength in the Length

Pallet damage also varies directly with the pallet strength in the length of the pallet (PSL). PSL is defined as the pallet flexure strength across the length of the pallet, which is the 48" direction of the pallets tested in the study.

For stringer pallets, PSL is estimated as the flexure strength of stringers, calculated by Equation 5.10 which is a modification of simple beam equation for uniform loading. The grade factor, f_g, derived by Wallin (1984) is used to reflect the strength reduction by varying the grade of stringers. The grading rules for stringers, derived during the PEP study, are used (Appendix D). The average grade of stringers, C, is to calculate the grade reduction factor.

$$PSL = \frac{1.333\,(B)\,(h^2)\,(F)\,(L)\,(f_g)}{S^2} \qquad [5.10]$$

Where:

PSL	=	pallet strength in length for stringer pallets, lbs
B	=	cumulative width of stringers, inches
L	=	length of stringer, inches
h	=	height of stringer, inches
fg	=	grade factor of stringer = $1\text{-}0.08(C)^{0.75}$
F	=	working stress in bending = 0.3 MOR of stringers, psi
S	=	free span = L-2, psi

For block pallets, the pallet strength in length is estimated by sum of the bending strength of the top panel deck in 48" direction, PSL_t, and the bending strength of bottom deck in 48" direction, PSL_b. The bending strength of the top panel deck in 48" direction is calculated by Equation 5.11.

$$PSL_t = \frac{1.333(F_bS/S)(L)(B)(h^2)}{(L-L_b)^2} \qquad [5.11]$$

Where:

PSL_t	=	top deck bending strength for block pallets, lbs
F_bS	=	allowable panel bending strength capacity parallel to the strength axis of structural panel, lb-In. per foot of panel width.
L	=	length of panel parallel to span direction, inches
B	=	width of panel perpendicular to the span, inches
L_b	=	length of the end block, inches
S	=	section modules of structural panel, in.^{3}/ft
h	=	thickness of structural panel, inches

The allowable panel bending strength of top deck, F_bS, and section modulus, S, are in Tables 2.1 and 2.1.1 of the Design Capacity of APA Performance Rated Structural-Use Panel (APA, 1991).

There are three bottom deck constructions for block pallets. These are panel base, perimeter base, and unidirectional base. Therefore, the bending strength of bottom deck in 48" direction is calculated separately.

For panel base, block pallets, the bending strength of bottom panel deck in 48" direction, PSL_b, is calculated by Equation 5.12.

$$PSL_b = \frac{1.333(F_bS/S)(L)(B)(h^2)}{(L-L_b)^2} \qquad [5.12]$$

Where:

PSL_b	=	bottom deck bending strength for panel base block pallets, lbs
F_bS	=	allowable panel bending strength capacity parallel to the strength axis of structural panel, lb-In. per foot of panel width.
L	=	length of panel parallel to span direction, inches
B	=	width of panel perpendicular to span, inches
L_b	=	length of the end block, 1 = L-L(b), inches
S	=	section modules of structural panel, in.^{3}/ft
h	=	thickness of structural panel, inches

For unidirectional pallets, the bottom duckboard bending strength in 48" direction depends on how the bottom deckboards are placed. If they are parallel to the 40" direction as the pallets in this study, the strength is zero. If they are parallel to the 48" direction, the bending strength of bottom deckboards is calculated by Equation 5.13.

For perimeter base, block pallets, the bending strength of bottom deckboards is also calculated using Equation 5.13. However, only butted boards are used to calculate the cumulative width of bottom deckboards.

$$PSL_b = \frac{2.133(b)(h^2)(F)(L)(f_g)}{(L-L(b))^2} \qquad [5.13]$$

Where:

PSL_b	=	bending strength for perimeter base and unidirectional base block pallets, lbs
b	=	cumulative width of bottom deckboards parallel to the direction of pallet length, inches
h	=	thickness of bottom deckboards, inches

L	=	length of pallet, 48 inches
f_g	=	grade factor, $[1\text{-}0.08\ (C)^{.75}]$
F	=	working stress in bending = 0.3 MOR, psi
C	=	average deckboard grade based on PEP grading rules
L(b)	=	length of corner block, inches

5.2.1.4 Fastener Withdrawal Resistance

In the PEP study, fastener withdrawal resistance is one of major factors affecting the resistance of pallets to damage. The empirical model of fastener withdrawal resistance was developed by Wallin (1984) and extensively evaluated by Osborne (1987). Fastener withdrawal resistance is calculated using Equation 5.14 according to Osborne (1987).

$$FWR = 11.2(FQI)(G^{2.25})(P) \qquad [5.14]$$

Where:

FWR	=	fastener withdrawal resistance (pounds per nail)
FQI	=	fastener quality index
G	=	specific gravity of nailing members (stringer or blocks)
P	=	penetration of threaded portion of shank

The fastener quality index (FQI) is calculated using Equation 5.15 according to Wallin (1984).

$$FQI = 221.24(WD)[27.15(TD-WD)(H/TL)+1] \qquad [5.15]$$

Where:

WD	=	diameter of round wire or the equivalent round-wire diameter of square or rectangular wire
TD	=	thread-crest diameter of threaded and fluted nails
H	=	number of helixes or threads along the shank in the length of the threaded portion of shank
TL	=	length of threaded portion of shank

Total fastener withdrawal resistance in top deck is used as a candidate predictor in this study. The total fastener withdrawal resistance is the individual fastener withdrawal resistance multiplied by the total number of fasteners used in the top deck of the pallet.

5.2.1.5 Fastener Shear Resistance

During the PEP study, it was discovered that many damages to lumber deck pallets were caused by joint shear failures. Wallin proposed a fastener shear resistance factor, as a measure of the effect of joint design to the resistance to shear deformation in the construction. The fastener shear resistance (FSR) is calculated using Equation 5.16, which is developed by Wallin (1984).

$$FSR = \frac{61.925(FSI)(G)(T)(C)}{(MC-3)} \qquad [5.16]$$

Where:

FSR	=	fastener shear resistance in pounds
FSI	=	fastener shear index
G	=	average specific gravity of nailed member (duckboard or panel)
T	=	thickness of the nailed member, in inches
MC	=	moisture content of nailed member at the time of assembly
C	=	number of fastener couples in the joint or in the whole pallet.

Fastener shear index (FSI) is a relative measurement of fastener quality only related to the fastener characteristics and calculated by Equation 5.17.

$$FSI = \frac{263{,}260(WD)^{1.5}}{(3M + 40)} \qquad [5.17]$$

Where:

WD	=	diameter of round wire or the equivalent round-wire diameter of square or rectangular wire, in inches
M	=	MIBANT bend angle of fastener, in degrees

The number of couples per joint is dependent upon the number of fasteners in the joint. For lumber deck pallet, it is determined as follows:

1 fastener per joint = 0 couple

2 fasteners per joint = 1 couples

3 fasteners per joint = 3 couples

4 fasteners per joint = 4 couples

5 fasteners per joint = 5 couples

For panels, the number of fastener couples are assumed to be equal to the total number of fastener used in the pallet since each joint contain more than 3 fasteners.

5.2.1.5 Pallet Classification Number

In addition to the previously mentioned pallet structural properties, a pallet classification (PC) variable is added as another predictor. The pallet classification variable accounts for the effect of pallet classification on the pallet durability. The PC is assigned as follows:

PC = 1 for partial 4-way pallets

PC = 2 for 2-way pallets

PC = 3 for panel base, block pallets

PC = 4 for perimeter base, block pallets

PC = 5 for unidirectional base, block pallets

For each type of pallets, the above candidate predictors are calculated and used as one set of the observations in the multiple regression analysis.

5.2.2 Multiple Regression Analysis

The purpose of the multiple regression analysis is to find a reliable regression model to predict the regression coefficients in Equation 5.1 for all the pallet designs tested in this study based on the selected pallet structural properties discussed in section 5.2.1. The regression coefficients in Equation 5.1 for the total damage costs for different pallet designs are within a small range from 1.0443 to 1.1738. In order to obtain a sensitive data, the coefficients of total damage costs of different pallet designs are linearly scaled by minus 1 and multiplied 100, denoted as R. The R is used as the dependent variable, called damage cost index.

So far, we have one response variable and a set of predictors, shear through the thickness of panel at top deck (STT), bottom deck strength (BDS), pallet strength in length (PSL), fastener withdrawal resistance (FWR), fastener shear resistance (FSR), and pallet classification (PC). We want to determine the best subset of predictors and corresponding best-fitting regression model for describing the relationship between the dependent and independent variables. There are two goals that can be achieved. One is to find a model that gives the best prediction of dependent variable, given the predictors for some new observations. The second goal is to obtain valid estimates for one or more regression coefficients in a model and then make inferences regarding the corresponding parameters of interest. That is to quantify the relationship between one or more variables of interest and the dependent variable, controlling for the other variables. In this study, we focus on the strategy for selecting the best model since the primary goal of the analysis is prediction.

In order to achieve the goal, the following steps are proposed (Kleinbaum, 1987):

1. Specify the maximum model to be considered.
2. Specify a criteria for selecting a model
3. Specify a strategy for applying the criterion.
4. Conduct the specified analysis.
5. Evaluate the reliability of the model chosen.

The first step is to choose a maximum model in the process of the model selection. All other possible models, called restricted models, can be created by deleting predictor variables from the maximum model. The purpose of selecting a maximum model is to avoid type II error. It is natural to include the linear effects of all six predictors. The higher order terms are eliminated for simplicity. In addition, there is no evidence indicating that any pallet structural property has nonlinear relationship with pallet durability. The interaction terms of PC X PSL and PC X BDS are included since the effects of PSL and BDS may interact with the pallet classification. The reason for eliminating all other interaction terms is to avoid collinearity. In order to avoid moderate or severe collinearity, it is advised that no interaction terms should be considered unless a strong evidence suggested interaction (Kleinbaum, 1987).

The second step is to choose a selection criterion. Many selection criteria for choosing the best model have been suggested, such as coefficient of determination,R^2, F statistics, Fp, mean square of residual, MSE(p), and Mallow's C(p). R^2 is important, but may be misleading because adding even unusefull variables will invariably increase R^2. Another reasonable criterion for selecting the best model is the F statistics for comparing the full and restricted models. The third criterion is the estimated error variance for the restricted model, namely MSE(p). The smaller the MSE(p), the better the model. The C(p) criterion is very useful for determining how many variables to include in the model, since it achieves a values of approximately p+1 if MSE(p) is roughly equal to MSE(k) in which p and k is the number of predictors for maximum model and restricted model, respectively. Many times, the best model depends on the criteria used. In this study, R^2 and C(p) are used. The former criterion is helpful in deciding the size of the best model, while the latter provides an easily interpretable measure of predictive ability.

The third step is to choose a strategy for selecting variables. The forward selection and backward elimination methods are used.

A multivariate regression analysis is conducted by Statistics Analysis System (SAS). Table 5.8 provides the simple correlation matrix of all the predictors. The simple correlation matrix separately describes the strength of the linear relationship between two variables. In particular, the correlation r21 = -0.692, r31 = -0.614, r41 = -0.589 measure the strength of the linear association with the damage cost index, R, for each of PSL, BDS, STT taken separately. It can be seen that the PSL is the independent variable with the strongest linear relationship to R, followed by BDS and STT. However, the simple correlation matrix does not describe the overall relationship

Table 5.8 -- A simple correlation matrix of eight panel deck pallet design variables

Corr.	R	PSL	BDS	STT	PCXBDS	PCXPSL	FSR	FWR	PC
R	1.00								
PSL	-0.692	1.00							
BDS	-0.614	0.571	1.00						
STT	-0.589	0.626	0.514	1.00					
PCXBDS	-0.589	0.571	0.988	0.470	1.00				
PCXPSL	-0.517	0.694	0.493	0.262	0.586	1.00			
FSR	-0.296	0.431	0.205	0.003	0.265	0.412	1.00		
FWR	0.227	-0.481	-0.198	-0.637	-0.113	0.118	0.140	1.00	
PC	-0.134	0.106	0.160	-0.147	0.288	0.756	0.204	0.577	1.00

Note:

R = total damage cost index
PSL = pallet strength in length
STT = shear resistance through the thickness of the panel top deck
FWR = fastener withdrawal resistance
FSR = fastener shear resistance
PC = pallet classification number

of the dependent variable, R to the independent variables PSL, BDS, STT, etc. considered together. Therefore, the full model is analyzed and the result is found in Table 5.9. The model seems a best-fitting model with R^2 = 0.905, MSE(8) = 1.539, and P-value = 0.0327. However, this model is not reliable for the following reasons. 1) The 15 independent observations are too small to reliably estimate 8 regression coefficients. According to Kleibaum (1987), the maximum number of estimated regression coefficients are 5 for the 15 observations. 2) There is severe collinearity among the independent predictors. One of the predictor variables is an exact linear combination of the others if collinearity exists among the variables. The collinearity creates numerical problems and results in an unstable model. In order to detect collinearity, the eigenanalysis of the predictor correlation matrix for the full model is conducted, that is found in Table 5.10. According to Belsley, Kuh, and Welsch (1980), any condition index (CI) greater than or equal to 30 suggests the presence of moderate to severe collinearity. The condition index of 44.33 in Table 5.10 indicates a severe collinearity exists among these predictor variables. That means some predictors have to be deleted. One way of doing this is to check the variance proportions. A variance proportion indicates, for each predictor, the proportion of total variance of its estimated regression coefficient associated with a particular principle component which is a set of new variables that are the linear combination of the original predictors (Kupper, 1987). If more than one predictor has a high variance proportion in the principle component with a high condition index, it is possible that these variables contribute to the

Table 5.9 – The analysis of varince of the full model for predicting the total damage cost index for panel deck pallets

Source	DF	Sum of Squares	Mean Squres	F Value	PR > F	R-Square
Model	8	112.61	14.08	5.94	0.032	0.9048
Error	5	11.85	2.37			
Total	13	124.42				

Table 5.10 -- Eigenanalysis of the predictor correlation matrix for the eight-predictor model

Number	Eigen-value	Condition Index	Variance Proportions							
			PC	STT	BDS	PSL	FSR	FWR	PCXBDS	PCXPSL
1	3.663	1.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00
2	2.205	1.151	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00
3	0.952	1.839	0.00	0.00	0.00	0.01	0.22	0.02	0.00	0.00
4	0.739	2.199	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.05
5	0.287	3.638	0.00	0.51	0.00	0.02	0.03	0.00	0.00	0.00
6	0.134	5.131	0.01	0.36	0.00	0.10	0.68	0.73	0.00	0.04
7	0.018	8.789	0.11	0.05	0.01	0.85	0.00	0.09	0.01	0.25
8	0.002	59.533	0.88	0.04	0.99	0.10	0.06	0.08	0.99	0.63

Note:

R = total damage cost index
PSL = pallet strength in length
STT = shear resistance through the thickness of the panel top deck
FWR = fastener withdrawal resistance
FSR = fastener shear resistance
PC = pallet classification number
PCXBDS = interaction between PC and BDS
PCXPSl = interaction between PC and PSL

collinearity problem (Kleinbaum, 1987). Table 5.10 indicates the collinearity may be due to the PC, PCXBDS, and BDS variables since the smallest eigenvalue is associated with the larger variance proportions for PC, PCXBDS, and BDS predictors. Hence, this full model is not a reliable model for future observations.

In order to overcome this problem, several reduced models are analyzed. By comparison of these different reduced models, it is found that the reduced model with the deletion of PC and PCXPSL is the best. The result of the reduced model is found in Table 5.11. The eigenanalysis of the predictor correlation matrix for the reduced model is shown in Table 5.12. The condition index is now 18.7 compared with the value of 44 in table 5.10, which indicates there is no severe collinearity in the model. Moreover, the number of estimated regression coefficients is reduced to 6, which provides a reliable estimates of regression parameters. Therefore, the model is more reliable in terms of predicting future events despite a reduction in R^2 to 0.708 from 0.905 compared for the full model. The parameter estimates of the reduced model are also found in Table 5.11. The parameters seem to match physical reality. The negative signs indicate that the higher the pallet structural properties, the lower the damage cost index.

Based on the above analysis, the reduced model can be used as a prediction model. However, this does not mean that all the 6 predictors are needed for significant prediction of the damage cost index. To determine which of these 6 predictors are sufficient, the reduced model is analyzed by the forward selection and backward elimination methods. In the forward selection analysis, the significant level for entry is

Table 5.11 – The analysis of variance of 6-predictor model for predicting the total damage cost index for panel deck pallets

Source	DF	Sum of Squares	Mean Squares	F Value	PR > F	R-Square
Model	6	88.066	14.678	2.823	0.10	0.707
Error	7	36.396	5.199			
Total	13	124.46				

Parameter Estimates:

Variable	Parameter Estimates	Standard Error
Intercept	21.54798	5.94356
PCXBDS	-0.000617	0.0006635
STT	-0.05526	0.0491099
PSL	-0.00082	0.000511
FSR	-0.000133	0.00070
FWR	-0.000268	0.000272
BDS	0.0017	0.00266

Note:

R = total damage cost index
PSL = pallet strength in length
STT = shear resistance through the thickness of the panel top deck
FWR = fastener withdrawal resistance
FSR = fastener shear resistance
PC = pallet classification number
PCXBDS = interaction between PC and BDS

Table 5.12 -- Eigenanalysis of the predictor correlation matrix for the 6-predictor model of predicting the total damage cost index of panel deck pallets

Number	Eigenvalue	Condition Index	Variance Proportions					
			STT	BDS	PSL	FSR	FWR	PCXBDS
1	3.177	1.00	0.04	0.00	0.00	0.00	0.01	0.00
2	1.384	1.07	0.01	0.00	0.02	0.06	0.04	0.00
3	0.922	1.78	0.04	0.00	0.07	0.32	0.01	0.01
4	0.283	2.44	0.51	0.01	0.10	0.01	0.01	0.00
5	0.228	3.47	0.26	0.00	0.05	0.57	0.73	0.00
6	0.006	18.70	0.14	0.99	0.76	0.04	0.21	0.99

Note:

R = total damage cost index
PSL = pallet strength in length
STT = shear resistance through the thickness of the panel top deck
FWR = fastener withdrawal resistance
FSR = fastener shear resistance
PC = pallet classification number
PCXBDS = interaction between PC and BDS

0.5. The results show that the FSR fails to enter the model at the 0.5 significant level. The ANOVA table and estimated parameters for the model without FSR are summarized in Table 5.13. Compared with Table 5.11, the R^2 is slightly reduced from 0.708 to 0.706. It is noted that the F statistics for 5 predictor model is larger than the 6 predictor model. That implies that FSR does not significantly improve model prediction. Therefore, the FSR is deleted from the model. The best model is, therefore, represented by Equation 5.18.

$$R = \beta_0+\beta_1(PSL)+\beta_2(BDS)+\beta_3(PCXBDS)+\beta_4(FWR)+\beta_5(STT) \qquad [5.18]$$

The estimated parameters are also shown in Table 4.13.

In summary, the total damage cost index, R, can be predicted based on the selected pallet structural properties, such as pallet strength in length, PSL; bottom deck strength, BDS; fastener withdrawal resistance, FWR; shear through the thickness of the top panel deck, STT; and the interaction term of pallet classification and bottom deck strength, PCXBDS. Equation 5.18 is a generalized model for the 5 pallet classifications tested in this study. The predicted total damage cost index, R, then is linearly scaled to the regression coefficient "a" in Equation 5.1 by dividing 100 and plus 1. Therefore, the total damage cost as a function of test cycle is determined based on the pallet structural design instead of the handling test. From a given pallet design and its purchase price, it is then possible to determine the economic life by solving Equation 5.3.

Table 5.13 -- The analysis of variance of the 5-predictor model for predicting the total damage cost index for panel deck pallets

Source	DF	Sum of Squares	Mean Squares	F Value	PR > F	R-Square
Model	5	87.88	17.58	3.844	0.045	0.706
Error	8	36.58	4.57			
Total	13	124.46				

Parameter Estimates:

Variable	Parameter Estimates	Standard Error
Intercept	21.89085	5.3079
PCXBDS	-0.000594	0.00061
STT	-0.058145	0.04377
PSL	-0.000808	0.000477
FWR	-0.000301	0.0001925
BDS	0.00210	0.002440

5.2.3 -- Verification of the Structural Design Model for Panel Deck Pallets

The durability model of panel deck pallets includes two subset models. One is called the model of economics of use, which is used to predict the economic life based on short time handling test discussed in the section 5.1. The other is called the structural design model which is used to predict the coefficient in the model of economics of use based on pallet structural properties without the actual physical tests discussed in the section 5.2.

The structural design model is derived by multiple regression analysis. Based on the discussion in the section 5.2.3, this model is the best for predicting the durability of the pallet designs tested in this study. However, there is no assurance that the model can be applied to other samples or other panel deck pallet designs. If the model predicts well for other pallet designs other than the pallets tested in this study, the model is reliable. There are several methods available to evaluate the reliability of a statistical model: the follow up study, the split-sample analysis, and the holdout sample. The most compelling way to assess the reliability is to conduct a follow up study and test the fit of the chosen model to the new data. However, it is more expensive. The split-sample analysis is often used to achieve the purpose without a new study. But, it requires a relative large data set. In this study, the different pallet designs are relatively small and therefore the split-sample method is not a reasonable choice.

To evaluate the reliability of the structural design model (Equation 5.18), other two panel deck pallet designs with 6 replicates each were tested in the VPI "FasTrack" and the results were compared with the predicted values by the model from Equation 5.18.

These two pallet designs, provided by APA, are denoted as PD and OD, respectively. They are the same style: full 4 way, non-reversible panel deck pallet. There are four wheel openings in the bottom deck. The PD design has plywood decks and laminated plywood blocks, and OD design has OSB decks and laminated OSB blocks. Figure 5.6 is a four view schematic diagram of the two pallet designs indicating component sizes as well as the location of openings. Table 5.14 is the detailed description of the two pallet designs. The average thickness of plywood deck is 0.7 inches, reflecting a nominal 23/32" dimension. The average thickness of OSB is 0.75 inches, reflecting the full 3/4" dimension. The strength axis of both plywood and OSB are parallel to the 48-inch pallet length. Both plywood and OSB are the APA rated sheathing, 48/24, exposure 1. The detailed descriptions of the fasteners used in the two pallets designs are shown in Table 5.15.

The handling test procedures for these pallets are the same as described in the section 2.1. Figure 5.7 is the plot of the total damage cost as a function of the test cycle for the two pallet designs. Equation 5.1 is fitted to the plot using least square criterion. The regression coefficients of the PD and OD pallet designs are 1.0537 and 1.0740, respectively. For the two pallet designs, it is possible to calculate the pallet structural properties discussed in the section 5.2.1. The calculated pallet structural properties are shown in Table 5.16. The pallet shear resistance through the thickness of the top panel deck, STT is calculated using Equation 5.7. The bottom deck strength, BDS, is calculated using Equation 5.9. The pallet strength in length, PSL, is calculated using Equation 5.11 and 5.12. The fastener withdrawal resistance, FWR, is calculated by Equation 5.14 and 5.15. The pallet classification number is assigned as 3 for block pallets with both panel top and bottom decks. Based on the pallet structural properties in Table 5.15, the total damage cost index of the two pallet designs, R, is predicted by the structural model in Equation 5.18. Therefore, the predicted regression coefficients for both the PD and OD designs are 1.0577 and 1.0774, respectively. For the PD design, the error of the prediction is 7.5 percent. For the OD design, the error of the prediction is 5.9 percent. Figure 5.7 is the plots of the actual and predicted total damage cost as a function of test cycle. This verifies the model may be reliable for the future predictions.

It must be pointed out that the pallet designs used for developing the model did not include laminated OSB blocks. However, the blocks of the OD design were laminated OSB. In terms of the effect on the model prediction, the only difference between laminated OSB and plywood blocks is the specific gravity which is used to calculate the fastener withdrawal resistance (Equation 5.14). The specific gravity of laminated panel blocks cannot be easily determined from the panel grade. Furthermore, it is difficult to identify panel grade used in blocks in practice. According to Kollmann (1975), the specific gravity of plywood is a little higher than original wood. The specific gravity of wood species commonly used for manufacturing plywood is from 0.48 to 0.56.

Hence, the specific gravity of laminated plywood blocks was assigned 0.5 regardless plywood grade used in the model considering the gaps within the laminated plywood blocks. But, it was not clear that what specific gravity of OSB should be assigned to OSB blocks since no such blocks were used in the pallet designs to derive the model. According to APA, the specific gravity of OSB is 10 percent higher than plywood with the same panel grade. When the specific gravity of OSB blocks was assigned as 0.55, the error of the model prediction for the OD design is -15%. This implies the two problems: 1) the actual specific gravity of the OSB blocks was not 0.55 or/and 2) the Equation 5.14 was not applicable to OSB blocks. There was a visible swelling of the laminated OSB blocks due to the weathering of the blocks. Hence, the fastener withdrawal resistance in Table 5.16 was calculated based on the specific gravity of 0.45 for the OSB blocks, which is assumed that Equation 5.14 is applicable for OSB blocks. The assumption needs to be verified. In fact, one of the limitations of a regression model is that it has to be limited to the range of data used to derive the model. Otherwise, the accuracy of the prediction is very questionable.

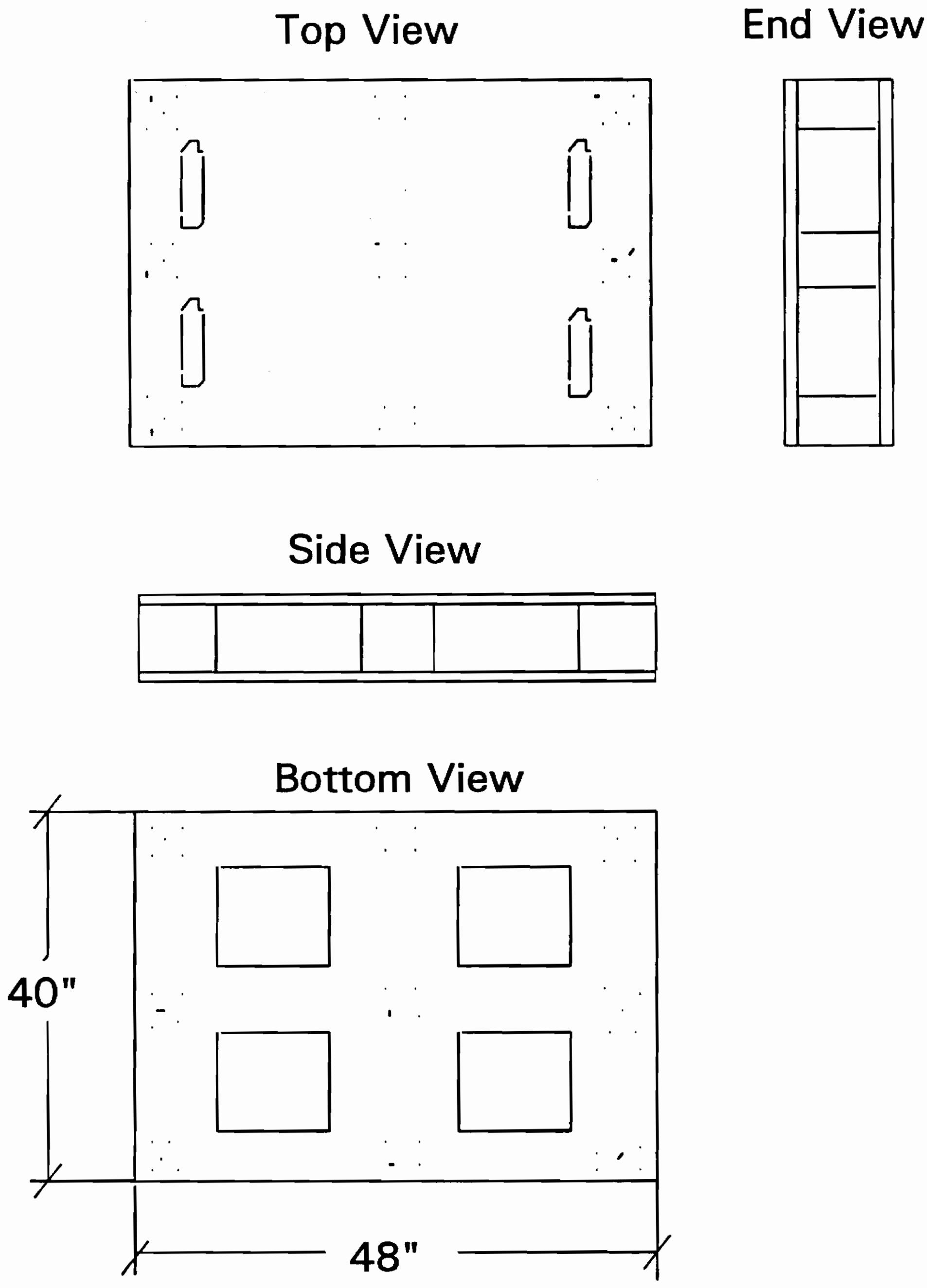


Figure 5.6 -- Schematic diagram of APA pallet design

Table 5.14 -- A general description of two APA pallet designs

Pallet Design	Top Deck			Bottom Deck			Block		Joint [1]	
	Panel Type	Panel Grade	Panel Thick (In)	Panel Type	Panel Grade	Panel Thick (In)	Type	Diam (In)	End	Center
PD	Ply	RS	23/32	Ply	RS	23/32	Ply	6X5.5	5	4
OD	OSB	RS	3/4	OSB	RS	3/4	OSB	6X5.5	5	4

Note:

1 -- number of nails per end or center block

Table 5.15 -- Description of fasteners used in the two APA pallet designs

Pallet Design	Nail Type	Length inches	Thread Length inches	Thread Diam inches	Head Diam. inches	Wire Diam. inches	Thread angle degree	Number Flutes	Mibant Angle degree
Ply	Helical	2.38	1.56	0.143	0.277	0.120	63	4	15
OSB	Helical	2.41	1.62	0.145	0.279	0.120	62	4	14

Table 5.16 -- Structural properties of the two APA panel deck pallet design

Pallet design	STT (lbs)	BDS (lbs)	PSL (lbs)	FWR (lbs)	PCXBDS (lbs)
PD	70.08	5227.49	1471.49	22539.2	20909.97
OD	58.50	5227.49	1471.49	18221.2	20909.97

Note:

PSL = pallet strength in length
STT = shear resistance through the thickness of the panel top deck
FWR = fastener withdrawal resistance
PC = pallet classification number
PCXBDS = interaction between PC and BDS

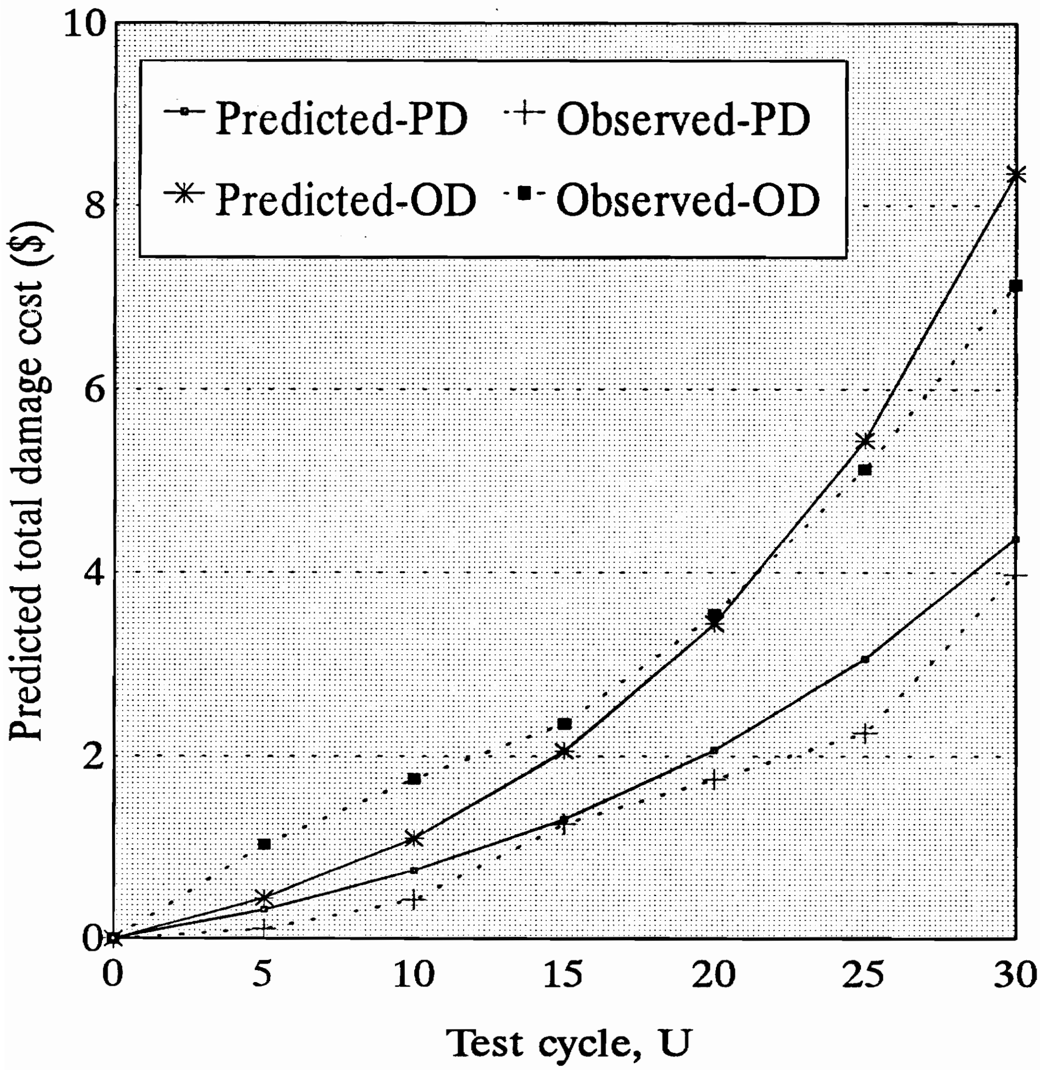


Figure 5.7 -- Plot of predicted and observed total damage cost as a function of test cycle for two APA pallet designs (PD-plywood deck and OD-OSB deck)

6.0 SUMMARY AND CONCLUSION

A method of predicting the durability of pallets, developed by Dr. Walter B. Wallin, was evaluated for predicting the durability of pallets with structural panel decks. It was determined that, while the basic concepts were applicable, the correlation between the structural design characteristics and the damage resistance contained in the original model were not.

In order to develop these correlations for panel deck pallets, 100 pallets were tested representing 15 different designs using a test procedure developed for this research. This protocol known as the VPI "FasTrack" simulates the stresses which occur in actual unit-load material handling system.

A method relating the pallet damage to damage cost was developed. from the observed damage to panel deck pallets, the average total damage cost (C_t) was related empirically to the number of uses (U) in the FasTrack as $C_t = a^U - 1$. The pallet is amortized and should be replaced when the average cost per use is a minimum. The number of uses, or trips, at which this occurs can be determined by differentiating a transformation of this relationship. The empirical factor "a" is unique for each pallet design. Using multivariate regression techniques, it was shown that the factor "a" can be determined from the following structural design features of panel deck pallets: (1) the strength of the pallet in length (PSL), (2) the strength of the bottom deck (BDS), (3) the pallet type (PC), (4) the fastener withdrawal resistance (FWR) at connections, and (5) the shear through the thickness of the structural panels (STT), using the following equation:

$$a = [\beta_0 + \beta_1(PSL) + \beta_2(BDS) + \beta_3(PCXBDS) + \beta_4(FWR) + \beta_5(STT)]/100 - 1$$

Where:

β_0 = 21.89085
β_1 = -0.000594
β_2 = -0.058145
β_3 = -0.000808
β_4 = -0.000301
β_5 = 0.002440

Several equations relating these performance characteristics of pallets to properties of the pallet components were also derived. An independent test of two pallet designs verified the accuracy of the procedure for predicting the durability of panel deck pallets.

The procedure for predicting the durability of panel deck pallets is shown in the flow chart in Figure 6.1. The pallet designer or user specifies the pallet design and purchase price as the inputs to the model. The model calculates structural performance characteristics of the pallet and estimates the total damage cost. The pallet designer can then obtain the economic life and the average cost per use of the pallet. In this study, the model permits the pallet designer to select the most efficient structures for use in unit-load material handling.

Based on the research, the following conclusions were drawn:

1. The average total damage cost as a function of test cycle for a pallet design was derived based on five samples. The variation of total damage cost varied at different cycle. Large variance occurred at lower cycles (less than 10 cycles) and small variance occurred after 10 cycles. The coefficient of variation of total damage cost after 10 cycles was in a range

of 7 percent to 30 percent. Based on the results of base pallet design which had 25 replicates, the average total damage cost of 5 samples represents the expected total damage cost with 85% confidence. Therefore, the average total damage cost, C_t, predicted using the equation: $C^t = a^U - 1$ should be interpreted with the confident limit.

2. The VPI "FasTrack" unit-load handling system and data analysis procedures can be used to evaluate the performance of different pallet designs used in the field material handling environments in terms of the number of damaged parts and the repair cost.

3. The damage factor "a" can be predicted using pallet design characteristics with R-square = 0.706. The effect of stringers and deckboards on the pallet durability of panel deck pallets was the same as they were in lumber deck pallets. However, the effect of fastener characteristics on the durability of panel deck pallets was smaller than they were in lumber deck pallets.

4. The durability of many pallet designs tested in this study were not significantly different. However, test results indicated that the different panel deck pallet designs resulted in the different durability of the pallets.

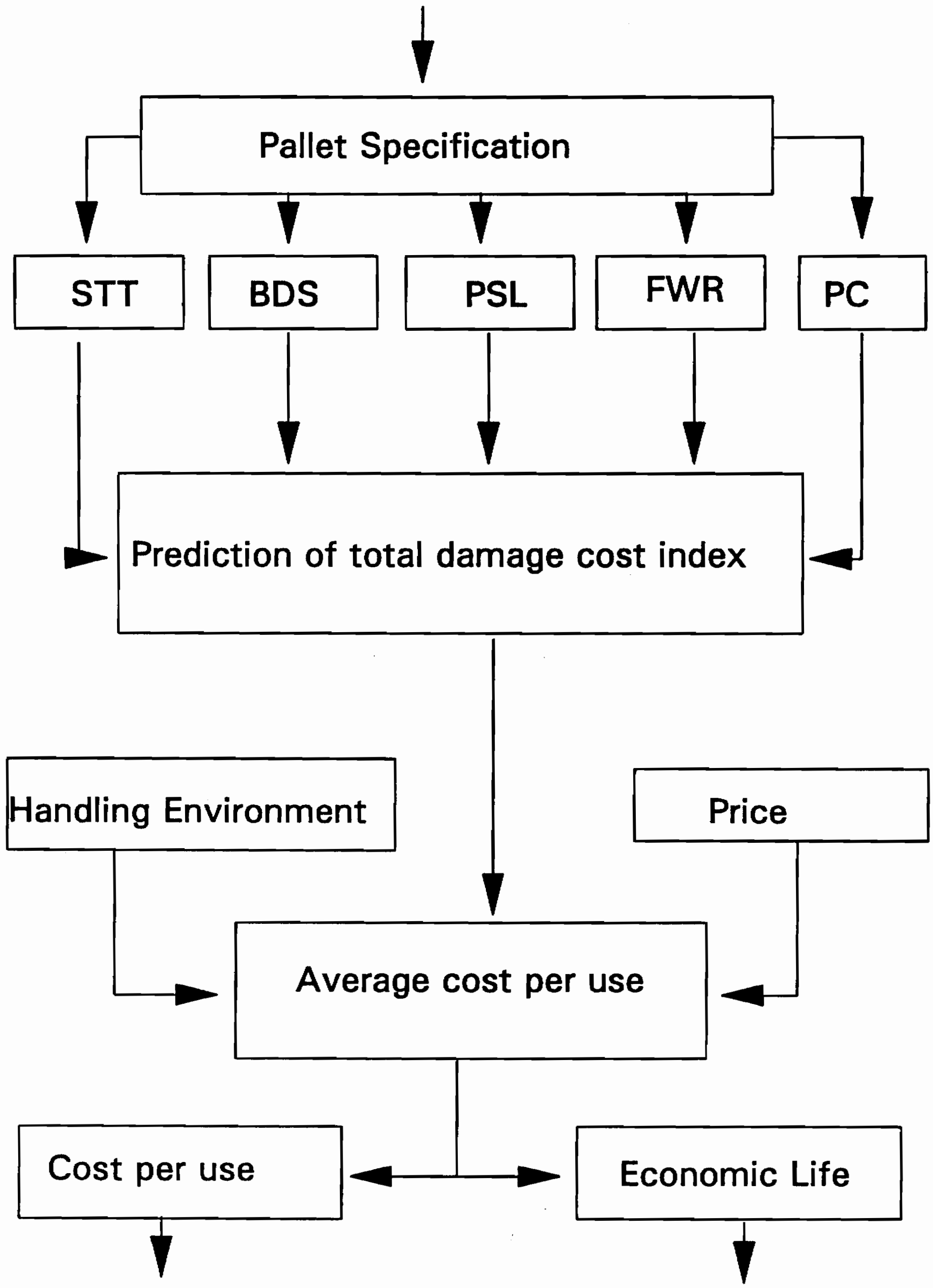


Figure 6.1 -- Flow chart of a durability model
for panel deck pallets

7.0 LIMITATIONS AND SUGGESTIONS

1. The estimates of the durability model is dependent on the repair criteria, repair methods, repair costs, and characteristics of the handling environment. Many of these parameters are constantly changing. Therefore, periodic studies are necessary to maintain the accuracy of the model. Standardization of repair practices would aid commerce and also improve the prediction accuracies of this durability model.
2. The model of economic use is based on the pallet price and the cost of pallet repairs. There is no consideration given to pallet disposal costs or any positive salvage values. These are becoming increasingly important factors relating to life cycle costs of pallets. Hence, it is recommended that these factors should be included in the economic model of the economics of pallet use in the future.
3. The relationships between pallet design characteristics and damage costs were developed based on only 15 pallet designs. Therefore, the model is somewhat limited to pallets of similar designs to those tested. More tests are therefore recommended to evaluate the effect of other pallet structural design properties on durability.
4. The published data of structural panel properties are designated for building application. Therefore, the data may not be applicable for the pallet construction.

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APPENDIX A: EVALUATION OF THE WALLIN PALLET DURABILITY MODEL

INTRODUCTION

The existing durability model in the PDS is a semi-imperial model initially derived from the PEP data by Dr. Walter B. Wallin (1984). The fundamental assumption of the model is that the performance of a pallet can be measured by cost-per-use. The lower the cost-per-use, the more efficient the pallet. In order to calculate cost-per-use, the total damage cost is assumed as

$$C_t = (F)\,(cb^S) \qquad [1]$$

Where:

C_t = total damage cost
F = damage frequency (i.e. number of damages)
c = economical coefficient
b = pallet design constant, b=1.5 for lumber deck pallets
S = damage severity level for the pallet

The damage frequency, F is assumed as:

$$F = a^U - 1 \qquad [2]$$

Where:

a = constant for a given pallet design
U = number of use, commercial trips

The a is defined as (1+R) where R is the damage rate.

According to Wallin, the damage rate, R, and damage severity, S, were only dependent on the pallet design and material handling environment. The R and S of 22 different pallet designs tested during the PEP study were derived. By comparing these pallet designs, the model used to predict the R and S were also derived. However, these procedures were not clearly documented.

In order to evaluate the model, an attempt will be made to rederive these relationships. The data used for this analysis was the original damage observations made during the PEP study.

DATA ANALYSIS

Table 1 is a summary of the damage data from the PEP study, which contains the number of uses, the number of damages, the damage severity for each type of pallets tested. The number of replicates of these pallet designs varied from 8 to 83 with the average of 45. The number of handling were varied from 60 to 216 with the average of 186. Variation existed not only between pallet designs, but also within a pallet design. According to Wallin, the damage frequency, F, was defined as the average number of damages sustained by the pallets, which was calculated by the total number of damages divided by the total number of pallets. The damage rate, R, for the pallet was calculated using the average of the number of handlings for the pallets based on the assumption in Equation 2. Thus, the damage rate and damage severity for all the pallets tested during the PEP study were obtained.

The method used to calculate the damage rate is questionable for the following reasons:

1) The number of damages were not clearly defined

2) The number of uses experienced by each pallet was different

3) The relationship between damage frequency and the number of use was not supported by the data

Furthermore, it was not clear how the damage severity per pallet in Table 1 was calculated.

In order to assess these problems, the damage recording procedures and original damage observations during the PEP study were analyzed.

How damages were recorded: The original damage observations for most of the PEP pallets are available. Table 2 is the damage data of the PEP type 20 pallet design.

Pallet damage was measured by the number of damage and severity. One damage was a single damage incident occurred at any part of the pallet. A damage severity was assigned to the damage incident based on the pre-described criteria. Along with the each damage incident was the number of handlings and the location indicating when and where the damage incident occurred, respectively. The damage locations were end deckboard, center deckboards, edge stringer, and center stringer.

Since each location has more than one pallet components, it is difficult to determine if the number of damage represented the number of pallet components or the actual damage incident from the data records. If no more than one damage incident occurred at every component, there is no problem. However, it is highly possible that more than one damage incidents could occur at the same component. Moreover, a damage incident may become more severe after successive handling. In these cases, it is not clear if the number of damage was recorded as a damage incident or restricted to one component regardless the number of incidents at that component. That needs to be verified because it affected the damage frequency.

How the number of damages were calculated: First, it is to determine how the number of damages in Table 1 was obtained. The number of damages by location were re-calculated based on the original damage data such as shown in Table 2. The results of the 5 PEP pallet designs are shown is Table 3. By comparison of the results with that of Table 1, it confirmed that the summary data in Table 1 was derived from Table 2. In fact, some miscalculations in Table 1 were found.

Second, it is to determine if the number of damage represent the number of damaged component or not. The percentage of damaged parts of the PEP pallets was reported in the PEP study as shown in Table 4. The data is the base for the verification. If the number of damages is assumed as the number of damaged components, it is possible to calculate the percentage of the damaged components for these PEP pallets based on the original data. The percentage of damaged components were recalculated by the number of damages divided by the number of components for each location. The calculated percentage of damaged pallet components is also shown in Table 4. The calculated results are very close to that reported by Wallin. Therefore, it concludes that the number of damages used by Wallin was the number of damaged components rather than damage incident. That indicated that more than one damages at one component were only considered as one damage and the severity was the combined severity for that component. Damage for any damaged component was recorded only by changing severity level after successive handing if it become more severe.

How the damage severity per pallet was calculated: According to Wallin, each damage was assigned a severity level. Based on the above analysis, the damage severity level in Table 2 was the severity of the damaged components rather than damage incidents. However, the description of damage severity level was not described in that way (Wallin, 1984).

The damage severity, S, defined by Wallin was related to repair cost as:

$$C = cb^{S} \qquad [3]$$

Where:

S = damage severity
C = damage cost for the severity S
c, b = regression coefficients

The relationship was derived from the repair data of pallet damage according to Wallin. However, such repair data has never been reported. Therefore, it is impossible to evaluate the relationship.

It was not clear how the damage severity per pallet in Table 1 was calculated during the PEP study. The following method is proposed and the results (Table 5) are compared with that in Table 1. It may conclude the following method could be used by Wallin.

First, the total damage costs of a pallet is calculated using Equation 4.

$$C_t = \sum_{i=1}^{N} (cb^{S_i}) \qquad [4]$$

Where:

C_t = total damage cost for an individual pallet
N = total number of damages sustained by the pallet
S_i = severity level of i^{th} damage

Second, the average cost per pallet is calculated using Equation 5.

$$C_d = \frac{\sum_{i=1}^{N} (C_{ti})}{N} \qquad [4]$$

Where:

C_d = average damage cost per pallet
N = total number of pallets of the same type
C_{ti} = total damage cost of i^{th} pallet

Finally, the damage severity per pallet is calculated using Equation 6.

$$S = \frac{Ln(C_d) - Ln(c)}{Ln(b)} \qquad [6]$$

Where:

S = average severity per pallet
C_d = average damage cost per pallet
c, b = coefficients in Equation 3

Based on the original damage data, the damage severity per pallet for all the PEP pallet designs are recalculated. The comparison of the calculated results with that in Table 1 for 5 PEP pallet designs is shown in table 5. Most of the calculated severities is similar to that reported by Wallin.

EVALUATION OF EQUATION 2 ($F = a^{U} - 1$)

According to Wallin, damage frequency was defined as the total number of damages per pallet after a certain number of uses. From the PEP original data, it was apparent that the total number of damages per pallet was significantly different among each pallet of the same type. As an example, the total number of damages sustained by pallets within type 20 varied from 0 to 8. The existing durability model assumed the number of damage per pallet within each type as the same. That is only possible if the damage frequency of a pallet was the average total number of damage for each type, that is the total number of damages divided by the total number of pallets for each type. The damage frequency of a pallet represented an expected mean total number of damages for each type of pallets, not for an individual pallet. Hence, the distribution of the total number of damages per pallet played an important roles in terms of comparing the damage frequency of different pallet designs. The differences in total number of damage between different type of pallets should be tested statistically based on the distribution of the number of damages each pallet sustained after a certain number of handling. If same number of uses and handling condition were assumed for all pallets within each type, the data in Table 2 serves as a bases for determining this distribution. The number of damages per pallets was the sum of damages sustained by the pallet during the test period. Based on the data in Table 2, it was determined that the number of damages per pallet appears 3-parameter Weibull distribution. It should be noted that the PEP pallets were not tested such that all pallets were subjected to the same amount of use or handling. Therefore, the distribution may change if all the pallets would have been used equally. It is questionable to compare the damage frequency based on the PEP test design.

The relationship between the damage frequency and number of handling for each type of pallets was evaluated using the original damage data. Such relationship could not be evaluated for each individual pallet because the data was not available. Taken the type 20 pallet design as an example, the damage data in Table 2 was sorted by the number of handling at which any damage had occurred. This sorted data is presented in Table 6. It was assumed that the data was generated in the way that all 32 pallets of the type 20 were subjected to the same number of handling at a similar material handling system and tested simultaneously. In fact, the number of handling experienced by each pallet varied from 60 to 309 handling during the PEP study. Nevertheless, this sorted data did provide a way to study the relationship between the damage frequency and the number of handling for a certain type of pallets. Equation 1 should be derived from this data. Figure 1 is the plot of the damage frequency as a function of the number of handling. The predicted damage frequency of the same pallet design using Equation 1 is also plotted in Figure 1. It is apparent that the Equation 1 does not accurately describe the relationship between damage frequency and number of handling, especially after 200 handling, which is the average of number of handling these pallets had experienced. At this point, it is difficult to determined if Equation 1 is correct or not since the data may also be incorrect. However, it can be concluded that the PEP test design was not suitable to derive the relationship. More controlled study is needed to be done.

EVALUATION OF TOTAL DAMAGE COST

After the total number of damages as a function of number of use was assumed, Wallin further assumed the average cost of the damages was independent on the number of uses. The average damage cost was determined based on the average severity. Hence, the total damage cost was the product of the damage frequency and the average damage cost as shown in Equation 1. The independence of damage severity and the number of uses was not determined during the PEP study. It was desirable to verify this because of its importance in the pallet durability model.

The sorted data in Table was used for the verification. The average damage severity per pallets after each handling was calculated using Equation 4, 5, and 6. Figure 2 contains the plot of average damage severity as a function of umber of handling for the type 20 pallet design. Other pallet designs were also verified and the plots showed the same trend as the type 20 pallet design. Hence, It confirmed that the average damage severity was independent of number of handling or uses. It is worth noticing again that the pallets were not experienced the same amount of handling. Therefore, more controlled study is needed to verify the relationship.

EVALUATION OF THE PREDICTION MODEL OF R AND S

From the data in Table 1, the R and S for all the pallet designs were calculated. Based on the characteristics of these pallet designs, the factors influencing the R and S were evaluated and a model was developed to predict the R and S from the pallet design and material handling environments.

The following pallet characteristics were believed responsible for the increase or decrease of the damage rate, R, and damage severity, S.

Pallet characteristics:

1) Fastener Withdrawal Resistance (FWR)

Equation 7 was proposed to calculated the fastener withdrawal resistance for a given pallet design.

$$FWR = \frac{222.22(FQI)(G^{2.25})(P)}{(MC - 3)} \quad [7]$$

Where:

FWR = fastener withdrawal resistance, Ibs
G = specific gravity of nailing members, stringer or blocks
P = the penetration of nail thread shank, inches
MC = moisture content of nailing member
FQI = fastener quality index

The FQI is calculated using Equation 8. The FQI reflects the relative quality of fasteners in terms of resistance to shank withdrawal regardless the actual joints.

$$FQI = 221.24(WD)[27.15(TD-WD)(H/TL)+1] \quad [8]$$

Where:

WD = diameter of round wire or the equivalent round-wire diameter of square or rectangular wire
TD = thread-crest diameter of threaded and fluted nails
H = number of helixes or threads along the shank in the length of the threaded portion of shank
TL = length of threaded portion of shank

2. Fastener Shear Resistance (FSR)

Equation 9 was proposed by Wallin to calculated the fastener shear resistance for a given pallet design.

$$FSR = \frac{61.925(FSI)(G)(T)(C)}{(MC-3)} \qquad [9]$$

Where:

FSR	=	fastener shear resistance,Ibs
FSI	=	fastener shear index
G	=	average specific gravity of nailed member (deckboards)
T	=	thickness of the nailed member, in inches
MC	=	moisture content of nailed member at the time of assembly
C	=	number of fastener couples in the pallet.

Fastener shear index (FSI) is also a relative measurement of fastener shear quality only related to the fastener characteristics and calculated by Equation 10.

$$FSI = \frac{263{,}260(WD)^{1.5}}{(3M + 40)} \qquad [10]$$

Where:

WD	=	diameter of round wire or the equivalent round-wire diameter of square or rectangular wire, in inches
M	=	MIBANT bend angle of fastener, in degrees

3. Joint Splitting Resistance (JSR)

Equation 11 was proposed to calculate the joint splitting resistance for a given pallet design.

$$JSR = \frac{675WD}{(74.17)(G^2)(ES^2)(T)} \qquad [11]$$

Where:

G = average specific gravity of stringers
ES = width of edge stringer, inches
T = thickness of deckboards, inches
WD = wire diameter of nails, inches

4. Strength of stringers (SS)

Equation 12 was proposed to calculate the flexural strength of stringers for a given stringer pallet.

$$SS = \frac{0.75(Y)(b)(h^2)(F)(g)(L)}{S^2} \qquad [12]$$

Where:

JSR = joint splitting resistance, lbs
b = cumulative width of stringer, inches
h = height of stringer, inches
L = length of stringer, inches
S = free span, inches
F = working stress in bending, psi
g = grade factor of stringer
Y = notch factor

The grade and notch factors were used to count for the strength reduction of stringers.

5. Deck strength (DS)

Equation 13 was used to calculated the deck strength for a given lumber deck pallet.

$$DS = \frac{2.11(Y)(b)(h^2)(F)(g)(L)}{S^2} \qquad [13]$$

Where:

DS	=	deck strength, lbs
b	=	cumulative width of top deckboards, inches
h	=	thickness of deckboards, inches
L	=	length of deckboards, inches
F	=	working stress in bending, psi
S	=	free span, inches
Y	=	ratio of top and bottom deckboard stiffness
g	=	grade factor of deckboards

6. Others

In addition to the above five calculated pallet structural properties, the overall shook grade and the specific deck construction methods, such as butted end boards, and selective placement of deckboards, were also believed responsible for the damage rate, R, and severity, S.

These properties were derived based on laboratory testing on these comparable pallet designs. Based on the specifications of the pallet designs tested during the PEP study, it is possible to calculate all the properties. Therefore, regression analysis could be used to determine the predictability of these properties on the R and S obtained from the PEP test. However, Wallin proposed 9 damage factors to modify the damage rate and severity of the "base pallet" as the damage rate and severity for a specified pallet design.

Damage Factors:

The damage rate, R, and severity, S, for the base pallet was 0.01 and 2.00, respectively. The increase or decrease of the R and S for other pallet designs over that of the base pallet was calculated. Then, all the structural properties of other pallet designs were compared with that of the base pallet. In this way, Wallin derived the following damage factors.

1. Fastener withdrawal resistance factor, F1

The fastener withdrawal resistance factor, F1, was derived as:

$$F1 = \frac{(19 - \frac{FWR_b}{FWR})}{20} \qquad [14]$$

Where:

FWR_b = fastener withdrawal resistance calculated for base pallet, lbs

FWR = calculated fastener withdrawal resistance for a specific pallet, lbs

This indicates that every 11,000 ponds increase of FWR will result in 1 percent increase in the pallet damage rate and damage severity.

2. Fastener shear resistance factor, F2

The fastener shear resistance factor was derived as:

$$F2 = 2 - \sqrt{\frac{FSR_b}{FSR}} \qquad [15]$$

Where:

FSR_b	=	Fastener shear resistance of base pallet, Ibs
FSR	=	Fastener shear resistance of a specific pallet, Ibs

This indicates that every 1000 ponds increase of FSR would cause about 1 percent increase in the pallet damage rate and severity.

3. Joint splitting resistance factor, F3

The joint splitting resistance factor was derived as:

$$F3 = \frac{(9 - \sqrt{\frac{JSR_b}{JSR}})}{10} \qquad [16]$$

Where:

JSR_b	=	Joint splitting resistance of the base pallet, Ibs
JSR	=	Joint splitting resistance of a specific pallet, Ibs

This indicated that every 100 ponds increase of JSR would cause about 3 percent increase in the pallet damage rate and severity over that of the base pallet.

4. Shook Grade Factor, F4

The average grade of base pallet was 2.23 (Wallin, 1984). F4 was used to account for the effect of shook grade on the damage rate and severity. F4 was derived as:

$$F4 = 1 - 0.12(AVG)$$

Where:
AVG = the average grade of a specific pallet design

it was noted that the F4 was 0.73 in stead of 1 when the average shook grade of the base pallet was used. A mistake may involved in the derivation of the equation.

5. Selective Placement Factor, F5

If the shook materials of a pallet are randomly placed, the damage rate and severity will increase by 10 percent (i.e. F5 =1.10). This implies that shook materials of the base pallet were selectively placed.

6. Stringer Strength Factor, R1

According to Wallin, stringer strength only affects the damage rate, not damage severity. The stringer strength factor was derived as:

$$R1 = 2 - \frac{SS_b}{SS} \qquad [18]$$

Where:

SS_b = Stringer strength of the base pallet, lbs
SS = Stringer strength of a specific pallet, lbs

This indicates that every 100 ponds increase of stringer strength will cause about 10 percent increase of the damage rate over that of the base pallet.

7. Deck Strength Factor, R2

According to Wallin, deck strength of a pallet does not affect damage severity, but damage rate. Deck strength factor was derived as:

$$R1 = 2 - \sqrt{\frac{DS_b}{DS}} \qquad [19]$$

Where:

DS_b = deck strength of the base pallet, lbs
DS = deck strength of a specific pallet, lbs

This indicates that every 100 ponds increase of deck strength will cause about 10 percent increase of the damage rate over that of the base pallet.

8. Deck Construction Factor, R3

According to Wallin, deck construction method only affect the damage rate. The deck construction factor was derived as:

$$R3 = 1.6 - \frac{(W)\,(S)}{180} \qquad [20]$$

Where:

W = cumulative width of end deckboards plus butted center deckboards, inches

S = number of stringers

If a pallet with 23 inches of endboards and no butted boards, F8 was 1.22 which indicates 22 percent of increase of damage rate over that of the base pallet.

9. Handling Environment Factor, R4

Handling environment affects both damage rate and severity, but in different extent. Material handling environments were categorized in to 7 levels in the existing model. These were excellent, very good, good, average, fair, poor, and very poor. F9 was assigned as follows:

	Exl.	Very good	Good	Avg.	Fair	Poor	Very poor
F9 (R)	1.1	1.2	1.3	1.35	1.4	1.5	1.6
F9 (S)	1.05	1.1	1.15	1.175	1.2	1.25	1.3

After all the factors were calculated, the damage rate, R and severity, S were calculated by Equation 21 and 22, respectively.

$$R = (F1)(F2)...(R3)(R4)(0.01) \qquad [21]$$

$$S = (F1)(F2)...(R4)(2.0) \qquad [22]$$

It is impossible to evaluate the derivations of these factors simply because these data is not available. In fact, the pallets selected during the PEP study were not possible to derive these equations used to calculate the damage factors. Many of the factors were interacted each other. Therefore, the model is extremely questionable for the further use.

Appendix Table A1 -- Summary of the pallet damage data supporting the existing pallet durability model

Pallet Design	No. of Pallets	No. of damages		No. of[2] handlings	Damages/pallet	Severity/pallet
		Deck	Spacer[1]			
20	32	48	10	212	1.813	4.332
1	37	111	11	196	3.297	3.536
2	70	107	36	161	2.043	5.339
3	46	174	31	167	4.457	4.709
18	48	41	6	177	0.979	4.052
28	52	63	18	185	1.558	3.817
48	25	16	9	196	1.00	3.772
19	34	83	7	207	2.647	4.018
4	50	174	50	216	4.480	5.613
5	52	177	42	177	4.212	5.469
22	12	21	4	168	2.083	5.224
13	83	356	61	184	5.024	5.021
26	48	220	44	193	5.500	4.618
14	40	140	7	189	3.675	4.669
16	45	170	38	192	4.622	4.757
15	39	56	16	196	1.846	3.653
9[3]	51	152	28	215	3.529	4.9
11[3]	45	73	44	193	2.600	4.766
12[3]	51	83	25	196	2.118	4.303
10[3]	43	67	10	198	1.791	4.556
21[4]	49	97	28	204	2.551	5.376
17[4]	8	15	8	62	2.875	5.284

Note:

1 -- stringers or blocks
2 -- average number of handlings per pallet of the same type
3 -- plywood deck pallets
4 -- block pallets

Appendix Table A2 -- The original damage data record of the type 20 PEP pallet design

Pallet ID	Total hdl.[1]	Damage hdl.[2]	ED		CD		ES		CS	
			F[3]	S[4]	F	S	F	S	F	S
1	111	111								
2	184	59	1	2						
3	267	31			1	4				
3		102	1	3						
3		102	1	2						
4	335	116	1	3						
4		116	1	4						
4		116					1	4		
4		148	1	6						
4		322			1	9				
4		322			1	6				
4		322					1	5		
5	341	104					1	5		
5		112			2	2				
5		112	2	2						
5		334					1	4		
6	126	53	1	2						
6		108			1	3				
7	255	116	2	2						
7		116			2	2				
7		198	1	5						
8	196	165	1	3						
8		165			1	4				
9	255	110	1	2						
9		198			1	2				
9		239					1	7		

Appendix Table A2 continued

Pallet ID	Total hdl.	Damage hdl.	ED		CD		ES		CS	
			F	S	F	S	F	S	F	S
11	277	277								
12	119	58					1	6		
13	98	98								
14	256	256								
15	234	121	1	2						
15		121			1	6				
16	322	126			3	2				
16		126	2	3						
16		270					1	7		
17	312	71	1	2						
17		77	1	3						
17		89			1	2				
17		89	1	2						
18	223	132	1	2						
19	144	144								
20	87	87								
21	151	151								
22	287	140	1	2						
22		202	1	6						
23	255	42			1	8				
24	258	258								
25	304	105	1	5						
25		162			1	2				
25		304					1	4		
26	126	43	1	4						
26		43			1	5				

Appendix Table A2 continued

Pallet ID	Tota 1 hdl.	Damage hdl.	ED		CD		ES		CS	
			F	S	F	S	F	S	F	S
27	126	114	1	4						
28	245	80			1	2				
29	60	60								
30	230	155								
31	123	123								
32	309	309							1	4
Total			29	78	19	58	8	41	1	4

Note:

1 -- total number of handlings of the pallet experienced
2 -- the number of handlings at which damage occurred
3 -- number of damages
4 -- damage severity
ED -- edge deckboards including both top and bottom
CD -- center deckboards including both top and bottom
ES -- edge stringers
CS -- center stringer

Appendix Table A3 -- **A comparison of the total number of damages by location calculated from the original damage observation and summarized by Wallin for 5 PEP pallet designs**

Pallet Design	Calculated No. of damage		Summarized No. of damage	
	Deck	Stringer	Deck	Stringer
20	48	10	48	10
1	97	11	111	11
28	62	18	63	18
11	83	50	73	44
9	134	25	152	28

Appendix Table A4 -- **A comparison of the percentage of damaged pallet components by location calculated from the original damage data and summarized by Wallin for 5 PEP pallet designs**

Pallet Design	Calculated percentage				Summarized percentage			
	ED	CD	ES	CS	ED	CD	ES	CS
20	48		10		22.4	12.9	14.1	3.1
1	97		11		39.5	29.1	13.5	2.7
28	62		18		17.1	7.9	15.4	3.8
11	83		50		26.6	17.0	37.8	20.2
9	134		25		56.1	12.3	23.5	7.8

Appendix Table A5 -- A comparison of damage severity per pallet of 5 PEP pallet designs calculated and summarized by Wallin

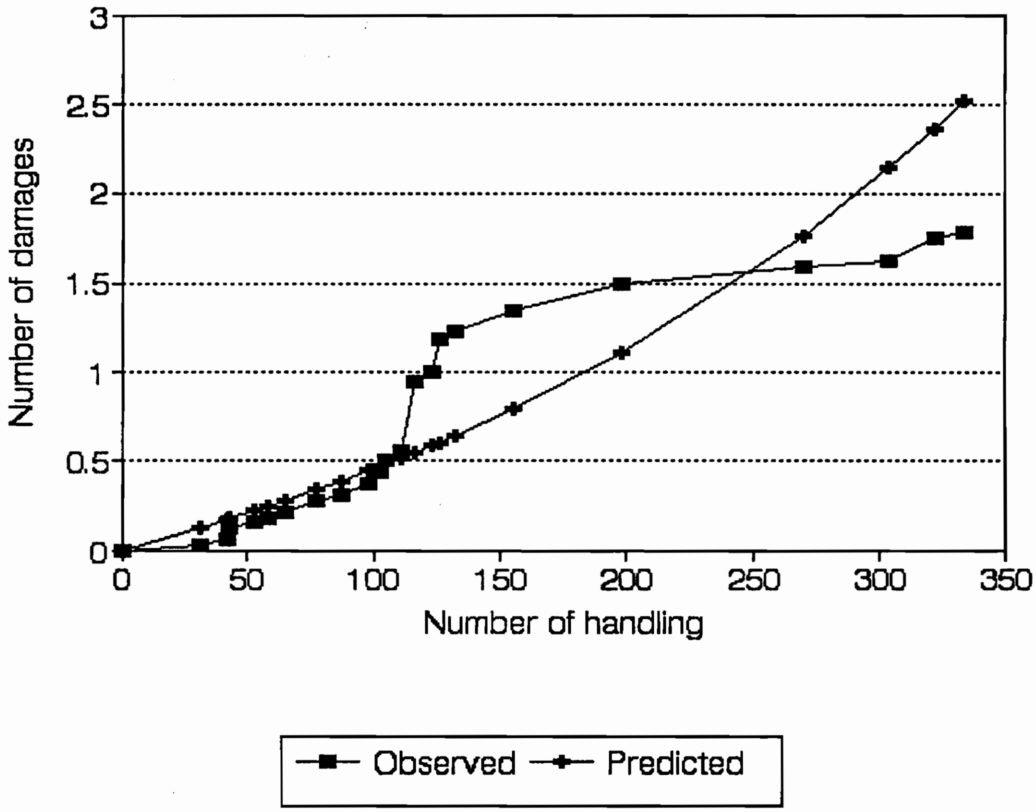
Pallet Design	Average severity by location				Severity/pallet	
	EB	CB	ES	CS	Cal.	Wallin[1]
20	3.299	4.7222	5.467	4	4.239	4.332
1	3.975	3.206	4.576	0	3.702	3.536
28	3.312	2.902	5.032	4	3.671	3.817
9	2.983	3.281	1.289	0.992	2.806	4.899
11	3.215	3.029	3.957	3.649	3.45	4.766

Note:

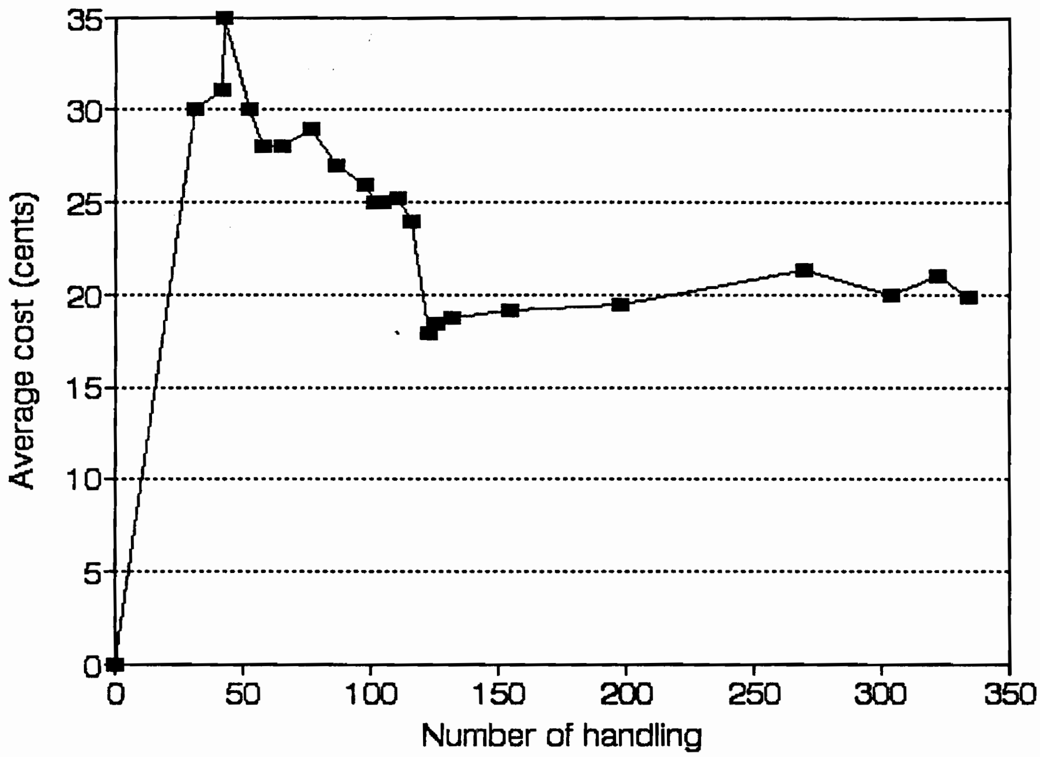
EB -- end deckboards
CE -- center deckboards
ES -- edge stringers
CS -- center stringers
1 -- Summarized severity by Wallin (1984)

Appendix Table A6 -- Damage frequency as a function of handlings to pallet type 20 in the PEP study

No. of handlings	Frequency	No. of handlings	Frequency
31	0.031	123	1.00
42	1.063	126	1.188
43	0.125	132	1.219
53	0.156	140	1.25
58	0.188	144	1.25
59	0.219	148	1.313
60	0.219	151	1.313
65	0.219	155	1.344
71	0.25	162	1.375
77	0.281	165	1.438
80	0.313	198	1.50
87	0.313	202	1.531
89	0.375	239	1.565
98	0.375	258	1.565
102	0.438	270	1.594
104	0.469	277	1.594
105	0.5	304	1.625
108	0.531	309	1.656
110	0.563	322	1.75
111	0.563	334	1.781
112	0.688		
114	0.719		
116	0.938		
121	1.00		



Appendix Figure A1 -- Plots of damage frequency as a function of number of handlings for the PEP type 20 pallet design



Appendix Figure A2 -- Calculated average damage cost as a function of number of handlings for the PEP type pallet design

Appendix B: Description of Damage Severity Levels Used in the PDS Durability Model

Damage Class	Severity Level	Description of the Damage	
		Pallet Part	Allowable Damage
Minor	1	Deckboards	Splits 3 to 6 inches long, which extend through a nailjoint.
		Plywood	Edge damage which penetrates from 1/4 to 1 inch.
		Stringer	No damage.
	2	Deckboards	Splits 6 to 10 inches long.
		Plywood	Edge damage 1 to 2 inches deep.
		Stringers	Splits 3 to 6 inches long (a 6-inch split from the end to the notch is a breas-code 7 or higher.
	3	Deckboards	Splits 10 to 20 inches long.
		Plywood	Edge damage 2 to 3 inches in depth.
		Stringers	Splits 6 to 10 inches long.
Moderate	4	Deckboards	Splits 20 to 30 inches; Diagonal breaks less than 10 inches long, and less than one-fourth of the width.
		Plywood	Edge damage 3 to 4 inches in depth.
		Stringers	Splits 10 to 20 inches long.
	5	Deckboards	Splits 30 to 40 inches in depth. Diagonal breaks which extend over one-fourth but less than one-half of either the width or the length of the part.
		Plywood	Edge damage 4 to 5 inches in depth.
		Stringers	Splits 20 to 30 inches long

	6	Deckbaords	Splits over 40 inches in length (48-inche parts); Diagonal breaks which extend over more than one-half of either the width or the length of the part.
		Plywood	Edge damage which is 5 to 6 inches deep.
		Stringers	Splits 30 to 48 inches long.
	7	Deckboards	A cross break or a longitudinal break with the parts in place and not more than one joint damage; A diagonal break with not more than one-eight of the part missing, and not more than one joint damaged.
		Plywood	Edge damage deeper than 6 inches, or one edge stringer joint damaged.
		Stringer	Any break with the parts in place and not more than one joint damaged.
severe	8	Deckboards & Plywood	Any break of combinations of damages, which cause two joints of one part to be ineffective; Any break with more than one-eighth but less than one-half of the part missing. Any break with not more than one-half of the cross-section area of the part missing;
		Stringers	Any break which causes two joints in any one part to be ineffective.
	9	Deckboards & Plywood	Any break or combination of damages which causes three joints in one part to be ineffective; Any break with more than one-half of the part missing.
		Stringers	Any break with one-half or more of the cross-section area of the part missing. Any break which causes three joints in one part to be ineffective.

APPENDIX C: Specifications of Pallet Designs Tested

Pallet Design: Base Design

Description: Partial 4-way, 48"X40", nonreversible flush style

Stringers:
- Height: 3.875" Width: 2.5" Length: 48"
- No. of stringers: 3 Species: S.P. MC: green
- Grade: 3 Notch: 6"X9"X2-1/2"

Top Deck:
- Plywood Structural 1, Rated Sheathing
- Thickness: 19/32" Span Rating: 32/16

Bottom Deck:

No. of 6's:	5
Thickness:	3/4"
Width:	5-5/8"
Species:	Southern Yellow Pine
MC:	Green
Grade:	2

Fasteners:
- Top deck:
  - VPI No. 2348 No of nails: 51
- Bottom deck:
  - VPI No. 2348 No of nails: 51

Pallet Design: Design 1

Description: Partial 4-way, 48"X40", nonreversible flush style

Stringers:
- Height: 3.875" Width: 1.5" Length: 48"
- No. of stringers: 3 Species: Oak. MC: green
- Grade: 3 Notch: 6"X9"X1-3/4"

Top Deck:
- Plywood Structural 1, Rated Sheathing
- Thickness: 19/32" Span Rating: 32/16

Bottom Deck:

No. of 6's:	5
Thickness:	3/4"

Width: 5-5/8"
Species: Oak
MC: Green
Grade: 2

Fasteners:

Top deck:

VPI No. 2626 No of nails: 30

Bottom deck:

VPI No. 2626 No of nails: 51

Pallet Design: Design 3

Description: Partial 4-way, 48"X40", nonreversible flush style

Stringers:

Height: 3.875" Width: 2.5" Length: 48"
No. of stringers: 3 Species: S.P. MC: green
Grade: 3 Notch: 6"X9"X2-1/2"

Top Deck:

OSB Sturd-1-Floor
Thickness: 19/32" Span Rating: 20

Bottom Deck:

No. of 6's: 5
Thickness: 3/4"
Width: 5-5/8"
Species: Southern Yellow Pine
MC: Green
Grade: 2

Fasteners:

Top deck:

VPI No. 2348 No of nails: 51

Bottom deck:

VPI No. 2348 No of nails: 51

Pallet Design: Design 2

Description: 2-way stringer, 48"X40", Reversible flush style

Stringers:

Height: 3.875" Width: 1.5" Length: 48"

No. of stringers: 3 Species: S.P. MC: green
Grade: 3

Top Deck:
Plywood Sturd-1-Floor
Thickness: 19/32" Span Rating: 20

Bottom Deck:
Plywood Sturd-1-Floor
Thickness: 19/32" Span Rating: 20

Fasteners:
Top deck:
VPI No. 2991 No of nails: 30
Bottom deck:
VPI No. 2991 No of nails: 30

Pallet Design: Design 4

Description: 2-way stringer, 48"X40", Reversible flush style

Stringers:
Height: 3.875" Width: 1.5" Length: 48"
No. of stringers: 3 Species: Oak MC: green
Grade: 3

Top Deck:
OSB Rated Sheathing
Thickness: 23/32" Span Rating: 40/20

Bottom Deck:
OSB Sturd-1-Floor
Thickness: 19/32" Span Rating: 20

Fasteners:
Top deck:
VPI No. 2991 No of nails: 30
Bottom deck:
VPI No. 2991 No of nails: 30

Pallet Design: Design 8

Description: Full 4-way block, 48"X40", Reversible flush style

Blocks:
Type: Oak MC: Green
No. 9 Length: 4" Width: 4" Height: 3-3/4"
Top Deck:
Plywood Rated Sheathing
Thickness: 23/32" Span Rating: 40/20
Bottom Deck:
Plywood Rated Sheathing
Thickness: 23/32" Span Rating: 40/20
Fasteners:
Top deck:
VPI No. 2626 No of nails: 36
Bottom deck:
VPI No. 2626 No of nails: 36

Pallet Design: Design 10

Description: Full 4-way block, 48"X40", Nonreversible flush style

Blocks:
Type: Laminated plywood
No. 6 Length: 6" Width: 4" Height: 3-3/4"
No. 3 Length: 5" Width: 4" Height: 3-3/4"
Top Deck:
Plywood Structural 1 Rated Sheathing
Thickness: 23/32" Span Rating: 48/24
Bottom Deck:
Plywood Structural 1 Rated Sheathing
Thickness: 23/32" Span Rating: 48/24
Wheel Openings: No. 4 Size: 13-3/4"X11-1/2"
Fasteners:
Top deck:
VPI No. 3333 No of nails: 42
Bottom deck:
VPI No. 3333 No of nails: 42

Pallet Design: Design 13

Description: Full 4-way block, 48"X40", Reversible flush style

Blocks:
Type: Laminated Plywood
No. 6 Length: 7" Width: 5" Height: 3-3/4"
No. 3 Length: 5" Width: 5" Height: 3-3/4"
Top Deck:
OSB Sturd-1 Floor
Thickness: 23/32" Span Rating: 24
Bottom Deck:
OSB Sturd-1-Floor
Thickness: 23/32" Span Rating: 24
Fasteners:
Top deck:
VPI No. 3047 No of nails: 36
Bottom deck:
VPI No. 3047 No of nails: 36

Pallet Design: Design 7

Description: 48"X40", Non-reversible flush, full 4-way, 9 block, perimeter base

Blocks:
Type: Oak MC: Green
No. 6 Length: 6" Width: 4" Height: 3-3/4"
No. 3 Length: 4" Width: 4" Height: 3-3/4"
Top Deck:
Plywood Rated Sheathing
Thickness: 19/32" Span Rating: 32/16
Bottom Deck:
Species: Oak MC: Green
No. 2 Length: 40" Width: 4" Thickness: 3/4"
No. 3 Length: 39-3/4" Width: 4" Thickness: 3/4"
Grade: 3
Fasteners:
Top deck:
VPI No. 2496 No of nails: 42
Bottom deck:
VPI No. 2496 No of nails: 42

Pallet Design: Design 11

Description: 48"X40", Non-reversible flush, full 4-way, 9 block , perimeter base

Blocks:
- Type: Laminated plywood
- No. 6 Length: 6" Width: 4" Height: 3-3/4"
- No. 3 Length: 4" Width: 4" Height: 3-3/4"

Top Deck:
- OSB Rated Sheathing
- Thickness: 7/16" Span Rating: 32/16

Bottom Deck:
- Species: Southern Yellow Pine MC: Green
- No. 2 Length: 40" Width: 4" Thickness: 3/4"
- No. 3 Length: 39-3/4" Width: 4" Thickness: 3/4"
- Grade: 3

Fasteners:
- Top deck:
  - VPI No. 2496 No of nails: 42
- Bottom deck:
  - VPI No. 2496 No of nails: 42

Pallet Design: Design 15

Description: 48"X40", Non-reversible flush, full 4-way, 9 block, perimeter base

Blocks:
- Type: Laminated plywood
- No. 6 Length: 7" Width: 5" Height: 3-3/4"
- No. 3 Length: 5" Width: 4" Height: 3-3/4"

Top Deck:
- Plywood Rated Sheathing
- Thickness: 23/32" Span Rating: 48/24

Bottom Deck:
- Species: Southern Yellow Pine MC: Green
- No. 2 Length: 40" Width: 5-1/2" Thickness: 3/4"
- No. 3 Length: 37" Width: 5-1/2" Thickness: 3/4"
- Grade: 3

Fasteners:
Top deck:
VPI No. 3333 No of nails: 42
Bottom deck:
VPI No. 3333 No of nails: 42

Pallet Design: Design 6

Description: 48"X40", Non-reversible flush, full 4-way, 9 block, unidirectional base

Blocks:
Type: Oak MC: Green
No. 6 Length: 5" Width: 4" Height: 3-3/4"
No. 3 Length: 4" Width: 4" Height: 3-3/4"
Top Deck:
Plywood Rated Sheathing
Thickness: 7/16" Span Rating: 32/16
Bottom Deck:
Species: Southern Yellow Pine MC: Green
No. 2 Length: 40" Width: 5-1/2" Thickness: 3/4"
No. 1 Length: 40" Width: 4-1/2" Thickness: 3/4"
Grade: 3
Fasteners:
Top deck:
VPI No. 2626 No of nails: 36
Bottom deck:
VPI No. 2626 No of nails: 36

Pallet Design: Design 9

Description: 48"X40", Non-reversible flush, full 4-way, 9 block, unidirectional base

Blocks:
Type: Oak MC: Green
No. 6 Length: 5" Width: 4" Height: 3-3/4"
No. 3 Length: 4" Width: 4" Height: 3-3/4"
Top Deck:
Plywood Rated Sheathing

Thickness: 23/32" Span Rating: 40/20
Bottom Deck:
Species: Oak MC: Green
No. 2 Length: 40" Width: 5-1/2" Thickness: 3/4"
No. 1 Length: 40" Width: 4-1/2" Thickness: 3/4"
Grade: 3
Fasteners:
Top deck:
VPI No. 2626 No of nails: 36
Bottom deck:
VPI No. 2626 No of nails: 36

Pallet Design: Design 12

Description: 48"X40", Non-reversible flush, full 4-way, 9 block, unidirectional base

Blocks:
Type: Oak MC: Green
No. 9 Length: 4" Width: 4" Height: 3-3/4"

Top Deck:
OSB Rated Sheathing
Thickness: 19/32" Span Rating: 32/16
Bottom Deck:
Species: Southern Yellow Pine MC: Green
No. 3 Length: 40" Width: 3-1/2" Thickness: 3/4"
Grade: 3
Fasteners:
Top deck:
VPI No. 2348 No of nails: 30
Bottom deck:
VPI No. 2348 No of nails: 30

APPENDIX D: Grading Criteria for Pallet Shook

Grading criteria employed for stringers

Defects	Description	Grades of parts		
		2 & better	3	4
Size of Knot	Maximum portion of cross section affected	1/4 of cross section	1/4 of cross section	1/2 of cross section
Location of Knots	Over notch or in end 6" of the stringer	1/2" max. diameter	1/4 of cross section	1/3 of cross section
Clusters of Knots	Knots over 1/2" in diameter spaced 3" or less apart are measured as 1 defect	None	1/3 of cross section	1/2 of cross section
Type of Knots	Knot holes, unsound or loose knots, and holes	1/8 of cross section	1/6 of cross section	1/4 of cross section
Cross Grain	Slope of general cross grain	1" in 10"	1" in 8"	1" in 6"
	Max. dimension of local cross grain	1/4 cross section	1/3 cross section	1/2 cross section
Splits, Check, and Shake	Max. length singly or in combination	1/4 of length of part	1/2 of length of part	3/4 of length of part
Wane	Max. portion of cross section	16 units	32 units	48 units
	Portion of nail face width	3/16 of face	1/4 of face	5/16 of face
Decay	Max. portion of cross section	none	1/8 of section	1/4 of section
Pith	Length in face	None	full length	Full length
	Length boxed	None	1/3 of length	

APPENDIX D Continued

Grading criteria employed for deckboards

Defects	Description	Grades of parts		
		2 & better	3	4
Size of Knot	Maximum dimension across width of the board	1/4 of board width	1/4 of board width	1/2 of board width
Location of Knots	Knots in the edge and end 3" of the board	1/4" max. diameter	1/4 of board width	1/3 of board width
Clusters of Knots	Knots over 1/2" in diameter spaced 3" or less apart are measured as 1 defect	1/4 of board width	1/3 of board width	1/2 of board width
Type of Knots	Knot holes, unsound or loose knots, and holes	1/8 of board width	1/6 of board width	1/4 of board width
Cross Grain	Slope of general cross grain	1" in 10"	1" in 8"	1" in 6"
	Max. dimension of local cross grain	1/4 board width	1/3 board width	1/2 board width
Splits, Check, and Shake	Max. length singly or in combination	1/4 of board length	1/2 of board length	3/4 of board length
Wane	Max. portion of cross section affected at point of deepest penetration	16 units	32 units	48 units
		1/16 of cross section	1/8 of cross section	3/16 of cross section
Decay	Cross section deepest penetration	none	32 units	64 units
Pith	In face board boxed	None None	full length 1/3 of length	Full length

VITA

The author was born in Anhui, China on August 25, 1961. He grew up in the southern part of China where he attended high school.

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As an engineer, he was working on the processing techniques of engineered wood products at the Research Institute of Wood Industry, Beijing, China from 1984 to 1989. As a visiting scientist, he was part of a corporative project of the development of wood frame house for China at Wood Materials and Engineering Laboratory at Washington State University from 1989 to 1991.