The Development of a Reliability-based Strength and Stiffness Methodology for Panel-Deck Pallets

by

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Abstract

There are currently no reliability-based design procedures for panel-deck pallets. The objective of this research is to develop a reliability-based methodology to predict the strength and stiffness behavior of pallets constructed with plywood and OSB decks. Three-dimensional analytical models for panel-deck pallets will be developed using the ABAQUS finite element program. Sensitivity studies conducted with these models will identify important variables in developing simplified models for use on microcomputers. Reliability-based calibration of the simplified models will ensure that pallets are designed to a satisfactory level of safety.

Introduction

The use of pallets to store and handle goods has increased dramatically over the past four decades. In 1990, the production of new pallets exceeded 536 million units (NWPCA, 1991). Rough estimations place the current annual production of pallets with panel decks at 10 to 15 million units. Manufacturing these units consumes significant amounts of structural panels. In 1986, the estimated consumption of structural panels used in fabricating pallets and crates exceeded 400 million square feet (3/8" basis) (APA, 1987).

Although many types of structural panels are suitable for pallet decks (Kurtenacker, 1975), plywood and oriented strand board (OSB) are the dominant types used. Plywood-decked pallets have been found to provide excellent service in food manufacturing and distribution (Lyons, 1972). Results from the

Pallet-Exchange Program (Wallin, Stern, and Strobel, 1975) indicate that plywood pallets are more durable than pallets constructed with lumber decks. Plywood pallets sustain less damage and require fewer repairs. The smooth deck of plywood pallets can reduce damage to goods. Although plywood pallets have a higher initial cost, in many instances they are a better long-term investment because of longer service life.

Need for Research

The Pallet Design System for stringer pallets constructed with lumber decks was developed through a cooperative research effort of the National Wood Pallet and Container Association (NWPCA), the USDA Forest Service, and Virginia Polytechnic Institute and State University (VPI&SU) (Loferski and McLain, 1987). The first generation of this reliability-based structural design procedure, PDS-STRINGER, was completed in 1984 and is copywritten by the NWPCA. In 1988, PDS-BLOCK was released (McLeod, 1988). PDS-BLOCK can be used to model block pallets. PDS is currently the only reliability-based design system for wood pallet structures.

At present, the stringer and block versions of PDS are usable for estimating the static strength, stiffness and durability of pallets constructed with only lumber decks. No reliability-based design system exists for panel-deck pallets. The lack of a standardized reliability-based design system for panel-deck pallets leads to over- and under-designed pallets. Over-design results in an inefficient utilization of our timber resources, while under-design can cause product damage and potentially unsafe conditions. Development of a reliability-based methodology for predicting the strength and stiffness of panel-deck pallets will provide a rational basis for designing efficient and safe pallets.

Objectives

The objective of this research is to develop a reliability-based strength and stiffness design methodology for panel-deck pallets. Three-dimensional analytical models will be formulated for block and stringer pallets using the finite element method (FEM). Verifying the accuracy of these models is essential. Sensitivity studies will be conducted using these analytical models. Systematically conducting sensitivity studies is a rational approach for reducing the degrees of freedom required to effectively model pallet behavior. Variables which significantly influence strength and stiffness properties will be identified for inclusion in simplified models compatible with microcomputers. Reliability-based calibration of the simplified models is required to ensure that panel-deck pallets are designed to an acceptable level of safety.

Scope

The methodology to be developed will predict reliability-based strength and stiffness values for block and stringer pallets constructed with plywood or OSB decks. Strength and stiffness estimates will be based on pallet condition at the time of manufacture. The methodology will allow the user to analyze pallets subjected to partial-uniform, full-uniform, one-line, two-line, and three-line loads for the following support conditions:

1) pallet with fully supported bottom deck (STACK support condition)

2) pallet supported along the stringer in a rack (racked across deck (RAD) support condition)

3) pallet supported along the ends of the stringers in a rack (racked across stringer (RAS) support condition)

Load conditions are illustrated in Figure 1 and support conditions in Figure 2.

Analysis of full four-way, partial four-way, and two-way geometries of common pallet sizes will be possible. The methodology will include the capability to analyze block pallets constructed with four, six or nine blocks, and stringer pallets constructed with two, three, four, or five stringers. The following are specific pallet configurations to be modeled:

<u>Top Deck Configurations</u>

1) single panel

2) leading edge reinforcement (lumber or plywood strips)

3) cut-outs (hand-holds)

4) winged and flush designs

<u>Bottom Deck Configurations</u>

1) lumber and plywood strips

2) solid panel or panel with cut outs

3) winged and flush design

<u>Deck Spacers</u>

1) composite blocks (plywood and particleboard)

2) solid wood blocks and stringers

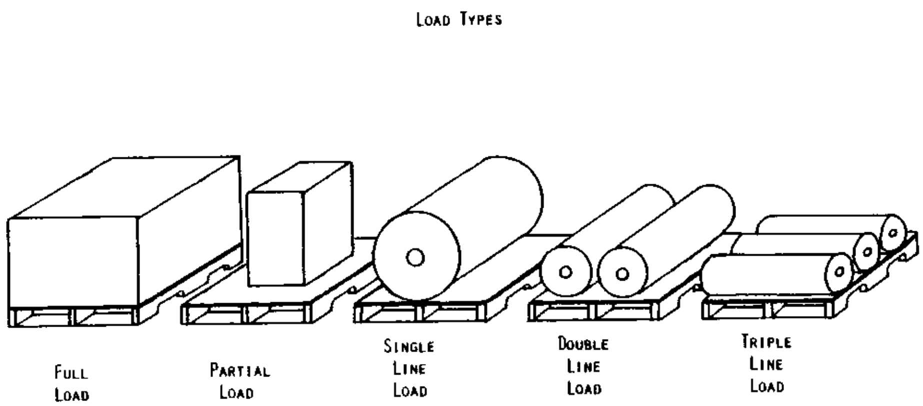


Figure 6 . Load types analyzed by PDS.

Figure 1. PDS-PANEL load types.
(copied with permission from Loferski, 1985)

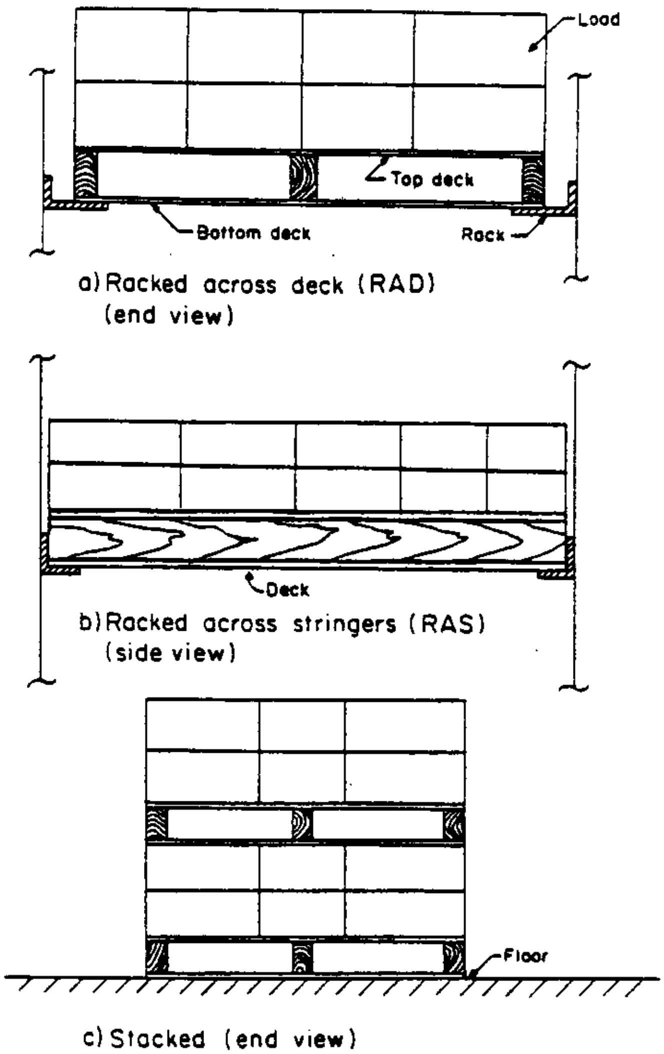


Figure 2. PDS-PANEL support conditions.
(copied with permission from Loferski, 1985)

Background

Plywood and OSB are considered acceptable materials for pallet decks. Because available literature on OSB use is scanty, most of this discussion regards plywood.

Minimum product specifications for two-way, partial four-way, and full four-way entry panel-deck pallets have been published by the NWPCA and the American Plywood Association (APA, 1980). These specifications are for pallets constructed with one or two panel decks and fabricated with mechanical fasteners. These specifications are not intended to provide procedures for the design of pallets. They are published primarily to assist pallet manufacturers and users in producing and specifying plywood pallets.

The "APA Industrial Use Guide - Pallets" presents guidelines for selecting and specifying plywood for pallet decks (APA, 1986). This publication contains tables which list maximum uniform load schedules for certain pallet geometries over a range of sizes. Maximum uniform load is based on plywood thickness and span rating. Pallet geometries considered are two-way entry stringer-type designs and four-way entry nine-block designs. Although these span tables can be used to design pallets, they are extremely limited in scope. This publication does not consider the racked across stringer support condition or partial four-way pallet geometry.

Elias (1986) studied the performance of plywood pallets for the racked across deck support condition. Design procedures were developed for certain stringer and block pallet geometries. These design procedures were based on standard beam formulas, employing empirical correction factors, based on interior support type and plywood grain direction. This design approach does not appear compatible with the reliability-based design methodology to be developed in this study and no attempt will be made to compare the two.

Load and Support Conditions

An on-site survey of 88 material handling environments was conducted by Goehring and Wallin (1981). Based on this survey, three classes were found to characterize the static loading of pallets:

1) uniformly distributed loads which completely cover the deck
2) partially concentrated or uniform loads which cover only a portion of the deck
3) concentrated line or point loads

Support conditions were also classified into three classes:

1) pallets loaded and dead piled in stacks (69%)
2) loaded pallets racked across deck (10%)
3) loaded pallets racked across stringers (21%)

Although it was observed that there was some shift away from these theoretical load conditions in service, no attempt was made to quantify differences between theoretical and actual load conditions.

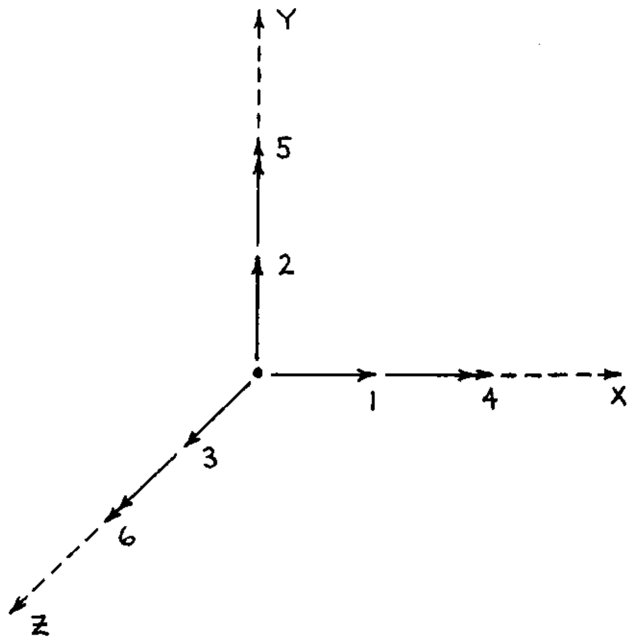
Subsequent studies by Fagan (1983) and Collie (1984) did consider the effects of load bridging on the theoretical load conditions. Load bridging was found to be dependent on load rigidity and pallet stiffness. This effect is relatively insignificant for very stiff pallets, becoming more severe with decreasing stiffness. Fagen (1983) concluded that for flexible pallets, assuming a uniformly distributed load can lead to the over-prediction of deflection by factors exceeding 50 percent.

Modeling Joint Behavior

Pallet joints in three dimensional space have six possible degrees of freedom or modes of action shown in Figure 3. Sensitivity studies conducted by Colclough (1987) showed that only out-of-plane rotation (rotation modulus) significantly influences the structural behavior of block pallets. The other stiffness components can be held constant with little loss of accuracy. Essential parameters for effectively modeling stringer-type pallets are the load carrying capacity, the translational stiffness (slip modulus), the separation or withdrawal modulus, and the rotational stiffness (rotation modulus) of the joint (Loferski, 1985).

The load carrying capacity of pallet joints has been extensively researched. Maximum joint capacity is determined experimentally by loading test joints to failure, with maximum load defining the load carrying capacity of the joint. Based on empirical data, Wallin and Stern (1974) formulated equations for calculating allowable lateral load and allowable withdrawal load for pallets joints constructed with stiff-stock and hardened steel nails.

The translational stiffness measures joint stiffness in lateral loading. The translational stiffness can be obtained empirically from load-slip curves or theoretically (Wilkinson, 1971, McLain, 1976).



1 = lateral translation parallel

2 = withdrawal

3 = lateral translation perpendicular

4 = twisting

5 = in-plane twisting

6 = out-of-plane rotation

Figure 3. Modes of action of a pallet joint.

The separation modulus and the rotational modulus are used to describe the stiffness of a nailed joint under load. The separation modulus is defined as the ratio of the applied withdrawal force to separation, while the rotational modulus is the ratio of the applied moment to the angular rotation (Kyokong, 1979). Because Kyokong (1979) formulated an equation relating the separation modulus to the rotation modulus, only one modulus of the two is necessary to model the stiffness of a pallet joint.

Loferski and McLain (1987) used spring elements to model the behavior of flexible nail joints found in stringer pallets. Joints were represented as beams supported by fictitious springs. Stiffness values derived from nail testing were assigned to the corresponding degree of freedom of each spring element.

Theoretical and empirical models for predicting the rotation modulus of block pallets were developed by Samarasinghe (1987). Using the matrix structural analysis approach, joint actions including head embedment, shank withdrawal and block edge crushing were idealized using a spring analogy. This analogy was applied to single and multiple fastener joints with excellent agreement between empirical and theoretical predictions.

Modeling Structural Panels

Structural panels are typically modeled as plates. Anisotropic plate theory is summarized thoroughly by Lekhnitskii (1968). Plate bending theory is based on the proposition that the thickness of a plate is thin with respect to its length and width dimensions. Two fundamental assumptions of "thin" plate theory are that the change in stress through the thickness of the plate is zero and material particles which form lines that are originally perpendicular to the mid-surface of the plate remain straight as deformation occurs, which is a kinematic constraint. For "thick" plates, shear effects must be considered.

The Kirchoff plate theory and the Mindlin plate theory can be used to model plates in bending (Bathe, 1982). The Kirchoff theory ignores shear deflections and the straight lines remain perpendicular to the mid-surface during deformation. The Mindlin theory considers shear and lines normal to the mid-surface remain straight during deformation, but do not necessarily remain perpendicular.

An alternative technique to classical plate theory was used by Iyer (1989). The technique used idealized thin, orthotropic plates as an equivalent grid, suitable for matrix-displacement analysis. The matrix-displacement approach used is discussed thoroughly in work by Holzer (1985). This grid model was unique because it was extended to plates exhibiting material orthotropy and it also had fewer members than previous grid formulations. The maximum error between predicted and theoretical deflections for plywood and OSB plates was 20 percent.

The Finite Element Method

The finite element method is discused in work by Bathe (1982) and Cook (1981). In formulating a finite element model, the continuum (structure) is discretized or subdivided into finite elements. These elements are finite both in size and degrees of freedom. A model describing the behavior of the individual elements must then be formulated. In achieving this a parent element is generated for each element type that appears in the model. The elements are then assembled into a structural model.

The solution for a discrete model subjected to a given load condition is obtained by solving for displacements which correspond to the degrees of freedom of the structure. Solutions are typically obtained using numerical methods such as Newton-Cotes or Gaussian Quadratures (Bathe, 1982). Once solved, post-processing can begin. Post-processing involves steps such stress and strain computations, and calculation of reaction, nodal, and elements forces. Other parameters such as strain energy can also be calculated during post-processing.

Gerhardt (1985) used the finite element method to model the behavior of notched pallet stringers. Twelve-node isoparametric plane elements were used to model single- and double-notched green oak stringers. The fillet regions of the notches were modeled using a hybrid finite element. Results from the finite element analysis show excellent agreement with experimental values.

In this research, the ABAQUS finite element program will be used (Hibbitt, Karlsson, and Sorenson, Inc., 1989). This versatile program is capable of modeling a gamut of structures. In addition, this program is capable of modeling other engineering problems such as thermal or vibrational phenomena. ABAQUS functions as a batch program, with the main input file specifying options required by the user. The user has a large element library from which to select appropriate elements. This program should prove extremely useful in achieving the objectives of this research.

Reliability-Based Design

Pallet design requires a balance of safety and economy. Achieving this balance is often difficult because of uncertainties such as variability of material properties and member size, load inconsistencies, and approximations (simplifying assumptions) inherent in design models. Traditionally, simple safety factors were used to account for these uncertainties. However, probabilistic (reliability-based) methods are now preferred, providing rational design procedures which are more logically consistent and applicable to all sources of uncertainty.

Reliability-based design procedures for wood are discussed in work by Zahn (1977). The design format used in the Pallet Design System (PDS) is based on first-order second-moment (FOSM) methods (Loferski, 1985). Load effects (S) and resistance (R) distributions are characterized by the mean and the variance. Failure occurs when the load effects exceed the resistance. A satisfactory level of safety is achieved when the resistance is sufficiently greater than the load effects.

The safety index, Beta, is defined as the resistance divided by the load effects and is determined as follows:

$$\text{Beta} = \frac{\ln\left[\frac{\bar{R}}{\bar{S}}\right]\sqrt{(1+V_S^2)\,(1+V_R^2)}}{\sqrt{\ln\left\{(1+V_S^2)(1+V_R^2)\right\}}} \qquad (1)$$

Where:

R = mean resistance

S = mean load effects

V_S = coefficient of variation of S

V_R = coefficient of variation of R

Beta = safety index

Generally, as Beta increases in magnitude, the level of safety increases. In PDS, a numerical value was assigned to Beta based on calibration with existing pallet designs known to have satisfactory strength and stiffness (Loferski, 1985).

Methodology

The proposed methodology is based partially on static load design procedures developed for pallets constructed with lumber decks. While these procedures are generally assumed to be applicable to panel-deck pallets, significant differences exist between panel and lumber pallets. Panel-deck pallets exhibit bending about two directions. Rolling shear is a potential failure mode in the panels, initiating a punch-through problem unique to panel-decks. The complexity of the stack support condition is increased significantly because bottom decks constructed of both lumber and plywood strips and panels will be considered. These differences will be considered in model development.

Development of Analytical Models

Three-dimensional analytical models will be developed using the ABAQUS finite element program, exploiting quarter-symmetry of common pallet geometries. The ABAQUS program is well-suited for analyzing three-dimensional structures constructed of rigid, pinned, or flexible joints exhibiting linear and nonlinear behavior. Because there are numerous elements in ABAQUS which can be used to model pallet behavior, the following criteria have been established to assist in deciding which are best suited for achieving research objectives:

a) accuracy of the static solution

b) suitability of model for simplification and use on microcomputers

c) computer time required for program execution

d) degree of model complexity

e) time requirements for model development

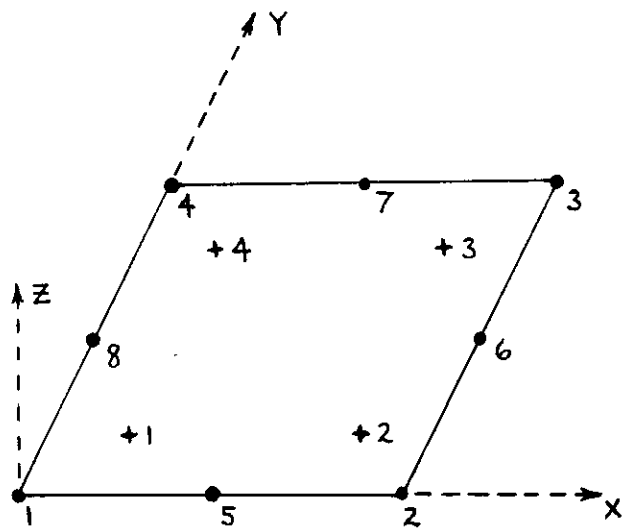
The static solutions of three-dimensional analytical models will require a high level of accuracy. Ideally, the models compatible with microcomputers will have the same high level of accuracy; however, simplifying assumptions which may be required for microcomputer compatibility could reduce accuracy.

The behavior of structural panels can be approximated using plate bending elements. The Mindlin plate theory has frequently proved more effective than the Kirchoff plate theory (Bathe, 1982). Finite elements formulated using the Mindlin plate theory are good general purpose plate elements. Mindlin plate elements are isoparametric. In addition to modeling shear deformation, they can model both material and geometric nonlinear behavior. Mindlin plate elements can be effectively joined with other elements such as beam or spring elements. Discontinuities such as hand-holes and cut-outs can be modeled using superposition. The S8R Mindlin plate element in ABAQUS is shown in Figure 4.

Mindlin plate theory is applicable when transverse deflections are small. This is also true of the grid analogy used by Iyer which is based on Kirchoff theory. For wood-based composites, transverse deflection can not exceed 0.5 times the thickness of the plate (Superfesky, et. al., 1977). Although plywood pallet deflections under load can exceed this limitation (Elias, 1986), the Mindlin theory should remain valid if a finite element mesh having sufficient fineness is used.

Mesh fineness will be evaluated for plate elements which are suitable for modeling panel decks. A sequence of regular mesh refinements will be used, with the finest mesh containing all previous meshes. Results will be compared to ensure that solutions are converging either monotonically from below or nonmonotonically with mesh refinement. Convergence requirements are summarized by Bathe (1982). Deflection results will also be compared to experimental deflection values measured for plywood and OSB panels (plates) by Iyer (1989). Based on this evaluation, the best element and optimum mesh fineness for modeling panel decks will be determined.

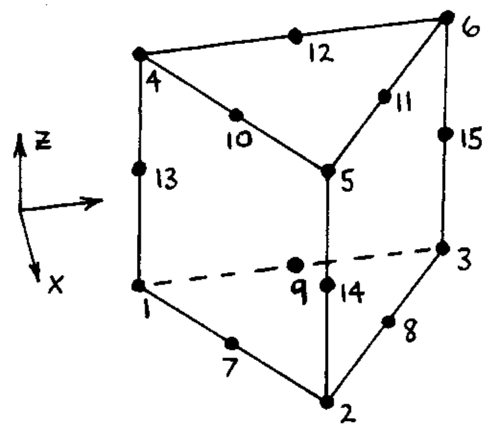
Three-dimensional solids appear well-suited for modeling stringers and blocks. The ABAQUS element library contains a wide variety of these elements. The C3D15V triangular prism and C3D27 brick elements shown in Figure 5 are good bending elements. Because deflections are interpolated in terms of nodal deflections, there are no kinematic constraints on these elements



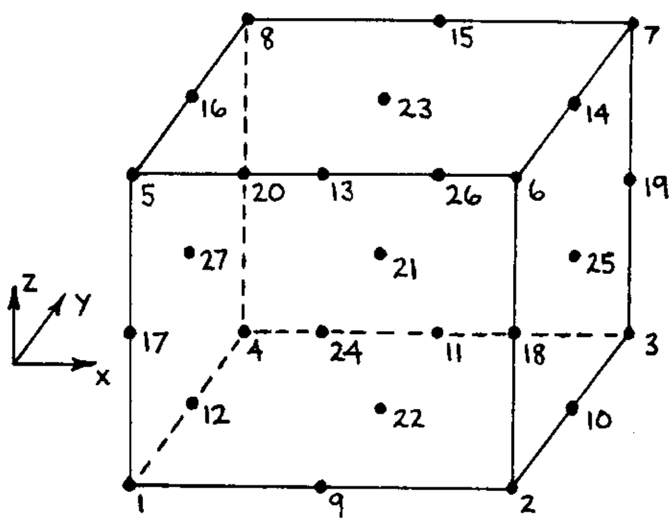
• Numbering of integration points for output

+ Numbering of reduced integration points

Figure 4. The S8R Mindlin plate element.



C3D15V



C3D27

• Node ordering on elements

Figure 5. The C3D15V triangular prism and C3D27 brick elements.

and relatively large deflections can be accurately measured. Three-dimensional solids interface well with other elements, especially gap elements. When modeling with these elements it is relatively easy to add additional elements in critical locations. Modeling discontinuities such as notches is also possible.

The primary disadvantage of using three-dimensional solids is that programs modeling even small, simple structures can become extremely large, requiring substantial amounts of execution time and large computers. Because adequate computer resources are available, blocks and stringers will be modeled using three-dimensional solids. Interfaces between deck spacer elements and deck elements will be filled by gap elements which allow nodes to be in contact if the gap is closed or separated if the gap is open.

Flexible joints will be modeled by zero-length springs or structural elements. If used, structural elements will be assigned adjusted modulus of elasticity values which reflect joint stiffness. Stiffness values for spring elements can be obtained from tests of nail joints (Loferski and McLain, 1987). Elements will reflect joint stiffness without the use of empirical correction factors.

Verification of Analytical Models

Rigorous experimental verification is necessary to ensure the correctness of the three-dimensional analytical models. Strength and stiffness values predicted by the models will be compared with those available in the literature. Work by Elias (1986) and Iyer (1989) should provide data for verification purposes. Additional testing of pallets will be required for common geometries over a range of sizes. This testing will be done for the full-uniform load condition and other load conditions as necessary.

Sensitivity Studies

Sensitivity studies will be conducted with the three-dimensional analytical models. These sensitivity studies will be used to evaluate the effect of pallet design variables on strength and stiffness. The variability of material property data provided by the APA will be evaluated. Material properties potentially required for analysis include the following:

Effective Section Properties of Panels

a) nominal thickness (in.)

b) effective shear thickness (psf)

c) effective area (in.^{2}/ft)

d) effective moment of inertia (in.^{4}/ft)

e) effective section modulus (in.^{3}/ft)

f) rolling shear constant (in.^{2}/ft)

Stiffness Properties of Panels

a) modulus of elasticity in bending in plane of plies

b) modulus of rigidity

~~Allowable~~ Stress Properties of Panels

a) extreme fiber stress in bending & tension in plane of plies

b) compression in the plane of plies

c) shear in plane perpendicular to plies

d) rolling shear in the plane of plies

e) bearing

Effective section properties are required for stresses applied both parallel and perpendicular to face grain. ~~Allowable~~ stresses and stiffness properties will be provided for each species group (face ply) and grade stress level.

Sensitivity studies will be used to evaluate joint stiffness. The six modes of action of a pallet joint shown in Figure 3 will be assessed to determine which modes significantly affect joint behavior. Stiffness values for these modes are typically obtained by experimentally testing nail joints. The bulk of testing has been conducted for pallets constructed with strip-type decking and literature regarding joint behavior of panel-deck pallets is scant. Further investigation is required to determine which values can be taken from literature and which will have to be experimentally measured.

The objective of these sensitivity studies is to identify important design variables, effectively reducing the degrees of freedom required to adequately model the behavior of panel-deck pallets. Additional studies will be conducted to evaluate the effects of using leading edge reinforcement, cut-outs (hand-holes), and composite blocks as opposed to solid wood blocks on pallet strength and stiffness.

Development of Simplified Models

Simplified models (programs) for use on microcomputers will be developed for block and stringer pallets. These programs are to be coded in "C," the computer language which the main PDS-PANEL program will be written in. These programs will be written so that they can be incorporated into the main program as a subroutine.

An appropriate finite element mesh will be selected to model panel decks based on findings from the sensitivity studies. The emphasis will be on selecting a mesh which is coarse enough for use on microcomputers, yet maintains an acceptable level of accuracy. The three-dimensional solids used to model blocks and stringers could prove to cumbersome for use on microcomputers. Other elements may have to be considered. The suitability of gap elements for use in the microcomputer environment is not known. It may be necessary to develop an alternative approach for modeling joint separation.

The simplified models will incorporate spring elements which model the behavior of flexible nail joints (Loferski and McLain, 1987). These elements will simulate joint behavior which is thought to be significantly influenced by lateral loads and rotational stiffness (rotational modulus) (Loferski, 1985, Colclough, 1987). This approach models the behavior of the real structure without the need for any empirical correction factors. It will provide the user with the capability to analyze common pallet geometries subjected to the selected load types.

Failure Criteria

Pallet failures are generally classified into two groups, serviceability failures and ultimate limit state failures. With regards to serviceability, failure occurs when the pallet does not perform adequately. A pallet deflecting beyond an allowable limit is a common type of serviceability failure. The ultimate limit state is associated with pallet strength properties such as bending strength and rolling shear. Exceeding an ultimate limit state can result in catastrophic failure. Sensitivity studies will determine which parameters govern failure, providing a rational basis for predicting the maximum allowable load a given pallet will support.

Calibration

A reliabilty-based method (Loferski, 1985) will be used to insure that pallets are designed to a satisfactory level of safety. To establish a satisfactory level of safety, the safety index, Beta, must be assigned an appropriate value. Beta is a function of load effect (S) and resistance (R) parameters, and can be determined using equation (1). Resistance input parameters are to be supplied by the APA. The mean resistance ($\bar{R}$) and the coefficient of variation of R (V_R) are minimal requirements, although complete distributions would provide a better understanding of how the input parameters vary.

Calibration is the process that will be used to assign a value to Beta. Existing panel-deck pallet designs which are known to have satisfactory strength and stiffness will be analyzed using Monte Carlo Simulation. This computer technique will generate data for a large number of structures of a given design required to accurately determine Beta. Potential pallet designs to be used for calibration will be identified by the APA and members of the NWPCA. This method will provide a level of safety which is uniformly reliable for the design methodology to be developed.

Timetable

This research project can be divided into a series of tasks which must be completed in achieving stated objectives. The timetables for completion of these specific tasks are presented in Table 1. The target date for completion of all tasks is May, 1993.

Report

This research will result in the development of a reliability-based methodology for predicting strength and stiffness properties of panel-deck pallets. Three-dimensional analog models will be developed using the ABAQUS finite element program. These models will be used in sensitivity studies to identify important variables in developing simplified models for use on microcomputers. The assumptions, equations, and procedures developed in this study will be contained within these simplified computer programs. A dissertation presenting the details of this research will be prepared.

Table 1. Timetable for the Development of a Reliability-based Strength and Stiffness Design Methodology for Panel-Deck Pallets

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                   1991                 1992              1993
 Task No.    M J J A S O N D  J F M A M J J A S O N D  J F M A M

   (1)       <--------->

   (2)       <----------------------------------------->

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   (4)         <--------------------------->

   (5)                        <------------->

   (6)                        <------------->

   (7)                        <------------->

   (8)                        <---------------------->

   (9)                        <---------------------->

  (10)                                              <----------->
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Task Description:

(1) Study plan formulation

(2) Review of literature

(3) Development of 3-D models using ABAQUS (requires that the ABAQUS finite element program be available)

(4) Experimental verification of 3-D models

(5) Sensitivity study: identifying important design variables

(6) Sensitivity study: evaluating material property effects on panel-deck pallet stiffness and strength

(7) Sensitivity study: evaluation of joint stiffness

(8) Development of simplified models and writing code for use on microcomputers

(9) Calibration studies (requires input from Dr. White's pallet survey regarding the in-service performance of common pallet designs)

(10) Dissertation preparation

Literature Cited

(1) American Plywood Association, 1987, Structural Panel Uses in Industrial Markets - 1986, Tacoma, Washington.

(2) American Plywood Association, 1986, APA Industrial Use Guide - Pallets, Tacoma, Washington.

(3) Bathe, K. J., 1982, Finite Element Procedures in Engineering Analysis, Prentice-Hall, Inc., Englewood Cliffs, N.J.

(4) Cook, R. D., 1981, Concepts and Applications of Finite Element Analysis, Second Edition, John Wiley & Sons, Inc.

(5) Colclough, R.G., 1987, The Development and Verification of Analysis models for Block-type Wooden Pallets, M. S. Thesis, VPI&SU, Blacksburg, VA.

(6) Collie, S. T., 1984, Laboratory Verification of Pallet Design Procedures, M. S. Thesis, VPI&SU, Blacksburg, VA.

(7) Elias, E. G., 1986, Plywood Pallet - In Rack Performance, R&D 85-27, APA, Tacoma, Washington.

(8) Fagen, C. B., 1982, Load-Support Conditions and Computerized Test Apparatus for Wood Pallets, M. S. Thesis, VPI&SU, Blacksburg, VA.

(9) Gerhardt, T. D., 1985, Strength and Stiffness Analysis of Notched, Green Oak Stringers, USDA Forest Service Research Paper, FPL 452, Madison, WI.

(10) Goehring, C. B., and W. B. Wallin, 1981, A Survey of loads, Loading Conditions, and Handling Environment Conditions for Wooden Pallets, Northeastern Forest Experiment Station, Forestry Sciences Laboratory, Princeton, West Virginia.

(11) Hibbitt, Karlsson, & Sorensen, Inc., 1989, ABAQUS - User's Manual, Version 4.8.

(12) Holzer, S. M., 1985, Computer Analysis of Structures: Matrix Structural Analysis - Structured Programming, Elsevier Science Publishing Co., Inc., N.Y.

(13) Iyer, R. G., 1989, A Novel Grid Analogy for Transversely Loaded Orthotropic Plates, M. S. Thesis, VPI&SU, Blacksburg, Va.

(14) Kurtenacker, R. S., 1974, Wood-base Panel Products for Pallet Decks, USDA Forest Service Research Paper, FPL 273, Madison, WI.

(15) Kyokong, B., 1979, The Development of a Model of the Mechanical Behavior of Wooden Pallets, Ph. D. Dissertation, VPI&SU, Blacksburg, VA.

(16) Lekhnitskii, S. G., S. W. Tsai, and T. Cheron, 1968, Anisotropic Plates, Gordon and Breach Science Publishers, N.Y.

(17) Loferski, J. R., 1985, A Reliability Based Design Procedure for Wood Pallets, Ph. D. Dissertation, Blacksburg, VA.

(18) Loferski, J. R. and T. E. McLain, 1987, Development of a Reliability- based Design Procedure for Wood Pallets, FPJ 37(7/8): 7-14.

(19) Lyons, B. E., 1970, Plywood Pallets, Research Report 107, APA, Tacoma, Washington.

(20) McLain, T. E., 1976, Curvilinear Load Slip Relations in Laterally Loaded Nail Joints, "Recent Research with Mechanical Fasteners in Wood," Proceeding No. p-76-16, Forest Products Research Society, Madison, Wisconsin (July).

(21) McLeod III, J. A., 1988, PDS - Block, unpublished research.

(22) National Wooden Pallet & Container Association, 1991, 1990, Estimated Production Report (New Pallets).

(23) National Wooden Pallet & Container Association and American Plywood Association, 1980, Specifications for Softwood Plywood Pallets, pp 61-72, Washington, DC.

(24) Samarasinghe, S., 1987, Predicting Rotation Modulus for Block Pallet Joints, M. S. Thesis, VPI&SU, Blacksburg, VA.

(25) Superfesky, M. J., H. M., Montry, and t. J. Ramaker, 1977, Floor and Roof Sheathing Subjected to Static Loads, Wood Science, 10(2): pp. 31-41.

(26) Wallin, W. B., and E. G. Stern, 1974, Design of Pallet Joints from Different Species, Northeastern Forest Experiment Station, Forestry Sciences Laboratory, Princeton, West Virginia.

(27) Wallin, W. B., E. G. Stern, and J. J. Strobel, 1975, Pallet-Exchange Program Research Findings Indicate Need for Pallet Standards, Wood Research and Wood Construction Laboratory Bulletin No. 134, VPI&SU, Blacksburg, VA.

(28) Wilkinson, T. L., 1971, Theoretical Lateral Resistance of Wood Nailed Joints, Journal of the Structural Division, A.S.C.E., 97(5): pp. 1381-1398.

(29) Zahn, J. J., 1977, Reliability-Based Design Procedures for Wood Structures, Forest Products Journal, 27(3): pp. 21-28.