

Modeling the Dynamic Interactions between Wood Pallets and Corrugated
Containers during Resonance

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(ABSTRACT)

The unit load is the form of most commercial and industrial products during storage and distribution. A simple form of a unit load, a palletized bulk bin is commonly used to transport fruit and vegetables from the point of harvest to processing facilities. These vibration sensitive products are often subjected to damaging vibrations during this period. Most damage occurs during the large accelerations associated with resonance, which occurs when the natural frequency of the unit load matches the input frequencies commonly encountered during transportation. A computer model, called RoPUL (resonance of palletized unit loads), of a palletized bulk bin loaded with fruit, was developed using finite element analysis techniques. Unit loads consisting of palletized bulk bins of apples and peaches were tested and RoPUL was found to accurately predict the resonant frequencies of these loads. Using RoPUL, the effects of product mass, container design, and pallet design on natural frequencies can be analyzed. As the input frequencies of most transportation modes is well documented, RoPUL can be used to help design a unit load to better protect vibration sensitive products during shipment.

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Dedication

To my family, Carol, Sophie, Alec, and the boys Henry, Cosmo, and Worm without whose love and support this work could never have been completed.

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1.0 Introduction

While passing through the distribution environment, products are subjected to a number of hazards. These hazards can generally be divided into two categories. One being environmental hazards such as temperature or humidity, and the other being mechanical hazards such as shocks and vibrations. Since its inception, protecting products from these hazards has been one of the primary functions of packaging.

As transportation and distribution systems have evolved over time so has the packaging used in them. For many centuries the wooden barrel was the most common form of packaging used for distribution (Soroka 1999). By the early 1900's corrugated containers were coming into common use, and they remain the most common type of distribution packaging. Since World War II, most goods packed in corrugated containers have been unitized, commonly with a wood pallet as the base, to aid in mechanical handling, shipping and storage. Today, most goods produced in the United States move through, at least part of the distribution system, in the form of a palletized unit load.

A major cause of shock damage is dropping of products during manual handling of individual packages. The increasing use of unit loads and mechanical handling has caused a corresponding decrease in the likelihood of shock damage. While shock damage can often be related to the type of handling used, vibration damage is generally related to the mode of transportation. Vibration damage usually occurs at resonance, when the product's, and/or unit load's natural frequency falls within the range of the forcing frequencies of the

mode of transportation being used. A variety of products, including electronics goods, and fresh fruits and vegetables are sensitive to vibration damage. Depending on the product, vibrations during the shipment of electronic equipment can cause surface abrasion, loosening of fasteners, metal fatigue, loss of calibration, and cracking in plastics (Caldicott 1991). Transportation vibration is also a major cause of fruit and vegetable damage. Low acceleration levels can cause bruising to fruits and vegetables, due to cell wall fatigue (O'Brien 1963).

Products and packages are often modified to protect products from vibration-induced damage during shipping. Many varieties of fruits and vegetables are harvested and shipped while still green and less susceptible to bruising. Singh (1992) found that changes in the primary packaging of fresh strawberries could affect the natural response of palletized loads of strawberries, and significantly reduce transportation damage. Urbanik (1978) used a multiple degree of freedom spring model to predict the natural response of a column of stacked corrugated containers. This model assumed that the product within the containers did not support any of the load, and as such did not influence the natural frequency of the stack. This model also ignored the affect of the pallet on which the boxes were stacked. Less is known about the affect of the pallet on the vibrational response of unitized loads. Lauer (1991), and Weigel et al. (1999), have found that changes in the design of the pallets on which the load is assembled can significantly affect both the natural frequency of the unit load, and the transmissibility of forced vibrations to the load. All of these studies have

examined the individual components of a unit load. Little is known about how these various components interact within the unit load. To efficiently design unit loads to protect products from vibration induced damage, more information is needed on how these interactions affect the response of unit loads to forced vibrations. Modeling the dynamic behavior of unit loads will provide industry with a new tool for designing pallets and containers that may minimize vibration related distribution problems.

2.0 Objective and Scope

2.1 Objective

The multitude of interactions between components in a unit load make it difficult to predict how that load will behave when subjected to forced vibrations such as those found in most transportation systems. However for many vibration sensitive products it is necessary to determine just that. The only reliable way to determine if a product will survive its trip through the distribution system is to perform trial shipments of actual products packaged, as they would be for shipment. The high cost of such tests generally limits their use for testing only those packaging systems most likely to succeed. The high cost of physical testing has at least, in part, driven the development of computer hardware and software, which can be used to create computer models that simulate the behavior of physical objects.

The objective of this research is to determine how components in the unit load interact during vibration excitation and to model, using finite element methods, model these interactions.

The SAP90 series of computer programs (Wilson et al (1992) were utilized for the development of the finite element model for predicting the natural response of palletized unit loads. This software was chosen for its ease of use, its ability to perform both static and dynamic analysis, and its availability in a PC format. At the most basic level the use of the SAP90 program for the analysis of a structure is a two-step process. First an input file is created which describes

the geometric relationship between components, along with information on the physical and mechanical properties each component. Once the input file has been created a static or dynamic analysis of the structure can be performed.

2.2 Scope

While most unit loads consist of a pallet holding multiple layers of containers each of which often holds a number of products, in its simplest form a unit load consist of a pallet, and a single container holding the product. The scope of this research is limited to this simple case of a single pallet holding a single container with product. There are a number of different products, which are transported using this system. The “Gaylord” container is an example of such a system widely used by industry to transport a variety of bulk goods ranging from auto parts to watermelons.

Unit loads are subjected to a variety of dynamic forces. While in the distribution system, the dynamic forces acting on the unit load can be generally classified either as vibrational loading or impact loading. While impact loading can and does occur from any direction, vibrational loading is typically caused by the reaction between vehicle tires and uneven road surfaces. As a result vibrational loading occurs primarily perpendicular to the road. It is assumed in this model that horizontal loading, while it does occur, has little impact on the vertical response of the unit load and will be ignored for the purposes of this model. In addition since the primary purpose of the RoPUL model is to predict resonant frequencies of the load, the impact of dampening will also be ignored,

since it influences the magnitude of the response but not the frequencies at which the response occurs. The central limit theory will allow the properties of components in the unit load to be represented by the average property of the particular material. That is to say that if the components that make up the unit load are assembled randomly the behavior of the unit will be best represented by the behavior of a model composed of the average component. This research will be limited to developing a two-dimensional model of a unit load consisting of a three-stringer pallet, a single container, with the container containing a variable number of layers of product. The model will also be limited to analyzing only the vertical vibrational resonances within the unit load.

3.0 Literature Review

3.1 Corrugated Containers

3.1.1 Modeling the static behavior of corrugated boxes

One of the earliest models for estimating the compressive strength of corrugated containers was developed by Kellicutt and Landt (1951). Using data from compression test of corrugated tubes, they developed an equation relating the combined ring compression strength of the materials forming the board and the container's perimeter, to the compressive strength of the container, which had the following form:

$$F = P_x \left[\frac{(a_{x2})^2}{(z/4)^2} \right]^{1/3} Z J \quad (1)$$

F = compression strength of the tube

$P_x = P_{11} + P_{12} + \square P_m$

P_{11} = ring compression strength of liner one in the cross machine direction (CD)

P_{12} = ring compression strength of liner two (CD)

\square = take up factor of the corrugated medium

P_m = ring compression strength of the corrugated medium (CD)

a_{x2} = constant for the flute style

Z = perimeter of the box

J = constant based on the type of manufactures joint and compensating for flaps

Maltenfort (1956) working for the Container Corporation of America, developed a set of linear equations based on the dimensions of the container, and the edgewise compression strength of the board liner, as measured by the then newly developed Concora Liner Test (CLT), for predicting the compressive strength of single wall containers. Based on tests of 296 containers the following relationship was established for each flute style, A, B, and C:

$$F = 5.8L + 12W - 2.1D + O \quad (2)$$

F = compression strength of the container

L = containers length

W = containers width

D = containers depth

O = constant based on flute style

for A flute $O = 6.5(\text{CLT-cd}) + 365$

for B flute $O = 5.4(\text{CLT-cd}) + 212$

for C flute $O = 6.5(\text{CLT-cd}) + 350$

CLT-cd = Compression strength for the CLT test in the cross machine direction

The main disadvantage of these early models was their dependence on strength values of the component paper used to form the corrugated board. These models were more useful to the board mills, and box manufacturers who had access to data on the component properties, than to the actual container users who had no way to independently validate if the board components were as specified. In addition it has been found that processing variations during the formation of corrugated board from its component materials can have a significant effect on the edge compression strength of the combined board (Batelka 1994).

This shortcoming was partly addressed by McKee et al (1961) with the development of a combined board edge compression test. McKee went on to develop an equation for the prediction of the compressive strength of a corrugated box based on the theoretical value of the compressive strength of edge supported plates:

$$P = a P_m^b \left[\sqrt{D_x D_y} \right]^{(1-b)} Z^{(2b-1)} \quad (3)$$

P = compressive strength of the box
 P_m = edge compression strength of the board
 D_x , D_y = flexural stiffness of the board in the machine and cross directions
 Z = perimeter of the box
 a and b are constants

Using regression analysis the constants, a and b, were determined to be 2.028 and 0.746 respectively. Because of the difficulty in measuring the flexural stiffness of the corrugated board the equation was further simplified using an empirically determined relationship between the flexural stiffness term and the caliper of the combined board resulting in:

$$P = 5.87 P_m \sqrt{h} \sqrt{z} \quad (4)$$

P = compressive strength of the box
 P_m = edge compression strength of the board
 Z = perimeter of the box
 h = the caliper of the combined board

For the package user the McKee equation had distinct advantages over the earlier equation developed by Kellicut and Maltenfort. First the uses of combined

board properties for the estimation of compressive strength compensated for variation in the combined board caused by the board forming process. It also allowed the user to independently confirm the mechanical specifications of the material.

Kawanishi (1988) took a different approach toward modeling the compression strength of corrugated boxes. Rather than base the compression strength of the container on the test of the mechanical properties of the board, Kawanishi developed a model based on a statistical analysis of the only the physical properties of the board from which the box was made including the moisture content. Also included in this model were terms to compensate for box size (perimeter), and print area. While this model does compensate for the effect of moisture content, the physical properties used in the model, as with the models used by Kellicut and Maltenfort, are more easily obtained by board manufactures or box fabricators than the end user.

3.1.2 Effect of moisture content

As stated above, one of the problems with most of the currently available models for the compressive strength of corrugated containers is that they lack the ability to adjust to changes in the moisture content of the container. A number of authors have looked at the affect of moisture content on the compressive strength of corrugated board and containers. Kellicut and Landt (1951) provided one of the first reports on the effect of moisture content on the mechanical properties of corrugated containers. They found that the same

relationship existed between the compressive strength of a container and its moisture content, for containers made of a variety of corrugated materials.

Based on tests of four box types they derived the following formula:

$$Y = b (10)^{-3.01x} \quad (5)$$

Y = compression strength of the box
b = compression strength of the box at 0% moisture content
x = oven dry moisture content of the box (expressed as a decimal)

describing the relationship between compression strength and moisture content.

Given compression strength at one moisture content, the compression strength can be at another moisture content can be calculated using the relationship:

$$P = P_1 \frac{(10)^{3.01x_1}}{(10)^{3.01x_2}} \quad (6)$$

P = compression strength to be determined
P₁ = known compression strength
x₁ = moisture content of box with strength P₁
x₂ = moisture content for box whose strength is to be determined

In addition they also produced a table of conversion factors from equation 6 for moisture contents between 5 and 21 percent. Ievans (1977) studied the effect that cycling humidity patterns had on palletized corrugated boxes. The main conclusion of this study was that in an environment with constantly fluctuation humidity conditions the moisture content of the palletized containers is closely related to the average relative humidity. It was also suggested that since the outside boxes in any pallet arrangement would gain moisture from high humidity conditions faster than boxes on the interior, that interlocking stacking patterns be used, which would allow the stronger interior boxes to contribute more to the entire stack strength.

levan's study indirectly points out the major problem with moisture content conversion equations, which is that while the moisture content of containers in use is usually not known the environmental conditions the container will be exposed to often are known. Moisture sorption isotherms relate the moisture content of materials to the relative humidity of the environment in which they are stored. Many sorption isotherm models have been developed for use on a variety of biological materials; however, few have been applied to modeling the sorption behavior of wood. Skaar (1988) discusses in detail a number of water sorption theories that have been used to develop moisture sorption isotherm models for wood. Simpson (1971) fitted sorption data from the *Wood Handbook*, which contained equilibrium moisture content (EMC) data for wood between the temperature of 5 and 210 degrees F, and relative humidity conditions between 5 and 98 percent to the Hailwood-Horrobin model. The results showed that the moisture contents predicted by the Hailwood-Horrobin model deviated less than 0.9 percent from the experimental data. Eagleton and Marcondes (1994) investigated the use of two sorption isotherm models, originally developed for use with food materials, for describing the moisture sorption behavior of fiberboard containers. They fitted EMC data on corrugated fiberboard between 1 and 40 degrees C, at a relative humidity between 43 and 96 percent, to the Brunauer-Emmett-Teller (BET) model and the Guggenheim-Anderson-de Boer (GAB) model. They found that the BET isotherm model generally did a poor job predicting the sorption behavior of corrugated paperboard. The GAB model provided estimates consistently within 1% of the measured moisture content.

3.1.3 Modeling the dynamic behavior of corrugated containers

Godshall (1973) studied the vibration transmissibility of corrugated fiberboard. He found that the vibration transmissibility and natural frequency of loaded corrugated fiberboard is dependant more on the properties of the corrugated medium used than the flute style. Urbanik (1978) modeled unitized stacks of containers on a pallet as a multiple degree of freedom vibration system to analyze the effect of transportation vibration on the stacked containers. Urbanik modeled each container as a single degree of freedom damped spring mass systems. The spring constant was calculated from static compression tests and the damping estimated from vibration tests. From this information the natural frequency of each container in the stack can be calculated and the transmissibility of an input vibration calculated. Urbanik's model failed to take in to consideration the ability of the pallet to act as another spring-mass system between the containers and the source of vibration.

3.2 Wooden Pallet

3.2.1 Pallet Design

Heebink and Forbes (1958) discussed the various material properties that can affect pallet design. Included among these were wood strength and decay resistance, moisture content, material defects (knots, splits, cross grain), manufacturing defects (off size lumber, wane, warp), and nail properties. Wallin, et al. (1976) developed a procedure for designing and evaluating wooden pallets

and skids. Their procedure was based on elastic design procedures commonly applied to structures. Three loading situations (uniformly distributed, concentrated midspan between stringers, and concentrated at midspan) in three support conditions (full support, racked across deck boards, and racked across stringers) were developed. To predict deflection and load capacity Wallin et al. (1976) modeled the pallet joints as either rigid or pinned connections. Since nailed pallet joints behave as semi-rigid connections between the two theoretical extremes Wallin et al conservatively recommended modeling as pinned connection for safety until more information on the contribution of the nailed joint to pallet performance becomes available. Mack (1975) developed a procedure for evaluating pallets racked across deck boards. Mack's model also was based on elastic theory and considered both the elasticity of the deck boards and the elasticity of the joints. However, his procedure is only applicable to concentrated loads applied at the centerline of the pallet. Kyokong (1979) applied matrix structural analysis to the analysis of pallets. The computer program he developed for pallet analysis modeled the pallet joint as a pinned connection restrained by a rotational spring. Mulheren (1982) developed a computer program called SPACEPAL, which can be used to analyze three-dimensional framed structures with either rigid or semi-rigid joints. His procedure, based on the matrix displacement method, modeled semi-rigid nailed joints as zero length spring elements whose stiffness was determined experimentally. Loferski (1985) developed a reliability based design procedure for wood pallets under static load conditions. Lauer (1991) and Weigel et al (1999) found that the design of a pallet

could significantly affect its response to forced vibration. These studies of pallet sections found that both the pallet's deck board stiffness, and joint stiffness affected the pallet's response. In general Lauer (1991) and Weigel et al (1999) observed that the stiffer the deck boards and joints the higher the pallet's natural frequency and the lower the transmissibility. While both Lauer (1991) and Weigel et al (1999) showed that the stiffness of the pallet's joints does affect its response to vibration, they quantified it only for the theoretical extremes of pinned and fixed connections. Nailed pallets joints behave as semi-rigid connections.

3.2.2 Nailed Joints

Most pallets are assembled with nails or staples. According to Ehlbeck (1979) the factors thought to affect joint performance are: 1. the strength, stiffness, and geometry of the fasteners and wood components, 2. the joint configuration, 3. the loading conditions. The joint configuration includes the number of fasteners used and their placement (Ehlbeck 1979).

Loferski (1985) found that the joint displacement that most affected a pallet's racked deflection was also the out of plane joint rotation. Samarasinghe (1987) found that for block pallets, out of plane rotation of the joint significantly influenced the structural behavior of block pallets. The rotational stiffness of a joint is the ratio of the applied moment to the angular rotation of the side member at the pivot point. Loferski et al. (1989) modeled the rotational stiffness of nailed joints as linear elastic springs representing the stiffness of the nail withdrawal, head embedment, and wood compressing at the interface between the main and

side members. Withdrawal stiffness is the force required to withdraw a nail shank, per unit length from the main member. Nail head embedment is the force per unit depth of embedment. For a given joint material, the head embedment force is hypothesized to be a function of the nail head area (in contact with the joint), rim thickness, and included angle or fillet diameter. Because of the difficulty in directly measuring the edge compression stiffness during joint rotation, the edge compression stiffness was determined indirectly. Loferski's model parameters were predicted assuming a uniform rate of loading of the joint. Loferski initially assumed that the rotation modulus would be a function of the physical properties of the side member and the characteristics of the fastener. However, statistical analysis of the data indicated no significant difference caused by the type of fastener used (both were similar helically threaded nails). As a result, the final model predicted the withdrawal stiffness and head embedment stiffness of the nail as a function of the specific gravity of the side member only. Theoretically the type of fastener used would also affect the joint stiffness but the two types of fasteners used in this study were similar enough that the difference between the two was not statistically significant. Wilkinson (1976) found nailed joints to be stiffer under vibrational loading than under static loading. Kurtenacker (1965) found that the dynamic withdrawal resistance of nails and staples was significantly higher than the withdrawal resistance under static loading.

3.2.3 Dynamic modulus of elasticity of wood.

A number of researchers have investigated the use of dynamic techniques for determining the modulus of elasticity of wood. Much of the work has been directed at developing nondestructive techniques for determining the static modulus of elasticity of wood, and not in quantifying the relationship between loading rate and modulus of elasticity. Kollmann (1960) describe of using the natural frequency to calculate the elastic constants of wood. Kollmann's study found that the modulus of elasticity as measured in a static test was approximately 4% lower than that calculated from the materials natural frequency. James (1962) used an instrumented toughness tester to collect load-deflection information at loading rates of around 8 inches per second. James observed that the values of the modulus of elasticity of the hardwood species tested, averaged 11% to 24% higher than the values measured in static bending. Hearmon (1966) discussed the theoretical basis for using natural frequency to determine the elastic constants of wood in particular its application to the nondestructive testing of wood. DeBonis et al (1980) found no significant difference in the distribution of modulus of elasticity for No. 2 dense kiln dried southern pine 2 by 4 lumber, as measured at 0.2 inches per minute and at 5 inches per minute. Gerhards and Link (1986) while investigating the effect of loading rate on the strength of Douglas-fir 2 by 4 lumber, found an increase in the modulus of elasticity for loading rates between 3 pounds per minute and 300 pounds per minute. Cai et al (1999) in an investigation of using nondestructive

vibrational techniques for determining the modulus of elasticity of southern pine floor joist found that the average modulus for the lumber calculated from the lumber's natural frequency compared to that measured in a static bending test, was 4% higher when the lumber was in a green state, 13% higher when the lumber was air dry, and 3% lower for joists salvaged from a demolished building. They theorized that splits that had developed in the salvaged joists may have accounted for the lower than expected measurement by vibrational methods. While it is generally accepted that wood behaves stiffer at higher rates of loading such as those experienced during resonance, little work has been done to quantify the relationship.

4.0 Vibration model development

The SAP90 series of computer programs (Wilson et al (1992) were utilized for the development of the finite element model for predicting the natural response of palletized unit loads. Throughout the rest of this text the model of the Response of Palletized Unit Loads, will be referred to by the acronym RoPUL. This software was chosen for its ease of use, its ability to perform both static and dynamic analysis, and its availability in a PC format. To decrease the complexity of the modeling process each component of the unit load (product, container, and pallet), was first modeled independently, and then combined to form RoPUL. For each component, a generic space frame model was developed which described the geometric relationship between components. Using the

physical and mechanical properties of the specific components forming the unit load, specific models can be created from the RoPUL model.

The primary objective of this study was to develop a model for predicting the natural frequencies of palletized unit loads, which then can be used as a tool for developing unit loads that better protect products. In reality a unit load has numerous natural frequencies corresponding to different modes of vibration in different directions. The major source of input energy to produce vehicular vibrations (truck and railcar) is vertical discontinuities in the road surface. This combined with the basic structure of most vehicular suspensions causes vertical vibrations to be the primary cause of vibration related damage (Guins 1975). For the purpose of developing a tool for designing unit loads to prevent vibration-related damage, the primary mode of interest is the vertical mode of the unit load vibration. Lauer (1991) showed that a two-dimensional pallet section could be used in testing the response of the entire pallet structure, therefore a two dimensional representation of a unit load was used. This provided sufficient detail for modeling different unit load configurations while simulating the natural frequency of interest. The RoPUL model was developed utilizing a single type of element (a three-dimensional prismatic frame element) from the SAP90 element library. The frame elements beam-column formulation includes the effects of axial-bending, torsion, and shear-deformation (Wilson and Habibullah 1992). Thus providing a good representation of the wooden members of a pallet, and as will be discussed later, can be used to simulate the vibrational behavior of corrugated containers and products being carried in the containers. Translational

springs were used to describe the support conditions at structural connections between elements, such as the nailed joint between the pallet deck boards and stringers. Most of the interfaces between components in a unit load do not have a structural connection, such as the interface between containers and the pallet deck board, therefore these connections were not restrained from translational or rotational movement, within the plane of the structure. While these components often are not in contact with each other during resonance, the limitations of the software do not allow for this type of behavior between elements. Because this type of behavior does not affect the natural frequency of the system, this limitation should not affect the model's ability to predict these natural frequencies.

4.1 Modeling the product component of the unit load

In its simplest form, the vibrational response of a product can be simulated as a rigid mass supported by a mass-less spring. The two-dimensional model of the product consists of two frame elements; one placed vertically (a column) acting as the spring, and the other placed horizontally acting as the mass. The horizontal element would contain the entire mass of the product and would be rigid, while the vertical element would possess the elastic properties of the product but is relatively mass-less (Figure 1).

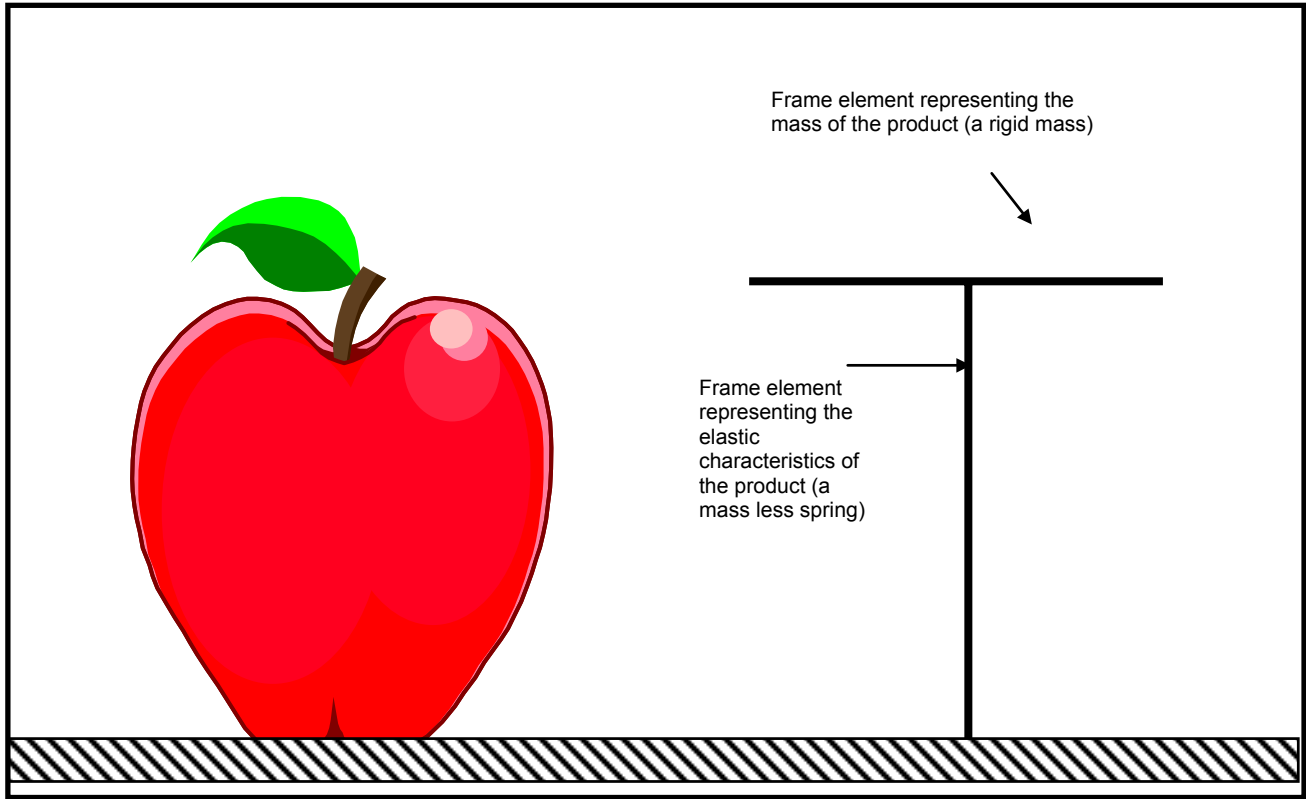


Figure 1. Schematic diagram of the RoPUL model of an apple

The natural frequency of a column supporting a mass can be described mathematically as a function of its effective stiffness.

$$(2\pi f_n)^2 = \frac{AE}{ml} \quad (7)$$

f_n = natural frequency (hz)

A = area (in^2)

E = Modulus of Elasticity (psi)

m = mass ($\frac{lb}{in/s^2}$)

l = column length (in)

This relationship can be used to determine the effective stiffness of the column element, representing the elastic properties of the product.

4.2 Modeling the container component of the unit load

In many packaged product systems within unit loads, the product in the bottom layer of containers rests on a single layer of corrugated which forms the bottom of the box. The same is true of products in bulk containers. Products are self-supporting and separated from the pallet, typically, by the layers of corrugated that form the bottom of the container. Using the spring-mass system analog, the bottom of the corrugated container can be viewed as a spring supporting the product. In RoPUL it is represented as a vertical frame element (a column) supporting the product model.

Cushioning materials like corrugated fiberboard tend to have nonlinear load-deformation characteristics. As the material is compressed either by a

heavier load or the same load applied more quickly the material is densified and becomes stiffer. To represent the corrugated sheet within RoPUL using a frame element with linear elastic properties, it is necessary to determine the stiffness of the corrugated fiberboard at the expected load level. Godshall (1968) found that the stiffness values obtained from cyclic loading of corrugated containers, around their static load levels, could be used to predict their natural frequency. This method of compression testing to determine spring constants, however, tends to underestimate the actual natural frequency of the loaded corrugated sheets (Godshall 1973). While compression tests can be used to obtain, a rough estimate of the stiffness values for dynamically loaded corrugated sheets, precise determination of stiffness values at low levels of deformation are best obtained using vibration tests of loaded corrugated sheets. For specific loading levels, the effective stiffness of corrugated can be determined from equation 7.

To confirm the suitability of using equation 7 to determining the corrugated board stiffness values for the RoPUL model, vibration testing was conducted on a 275 lb. c-flute board at three different levels of loading. The details of these tests are contained in Appendix D. From a single sheet of corrugated board ten 16-inch by 6-inch samples were cut. For the first test a 16-inch by 6-inch steel plate weighing 20.2 lb was placed on each sample in turn. The sample was then subjected to a vibration test sweeping from 5 hertz to 200 hertz. The point of maximum acceleration was used to determine the natural frequency of the loaded corrugated board. The test was then repeated using a 30 lb and a 40.2 lb

weight. Equation 7 was then used to determine the effective stiffness of the corrugated board at each load level.

Table 1. Effective stiffness of 275 lb c-flute at three load levels as calculated using Equation 7

Weight lbs	Mass Lbs/sec ²	Load area in ²	Column lth. in	Fn Hz	E PSI
20.2	0.05227	96	0.174	116	50.3
30	0.07764	96	0.174	114	72.3
40.2	0.10404	96	0.174	111	92.1

SAP90 was then used to create a RoPUL model of a corrugated board supporting a steel plate, matching the configuration of the vibration. The effective stiffness values calculated earlier were input for the corrugated board's modulus of elasticity. The predicted natural frequency was then compared to the measured natural frequency from the vibration test.

Table 2. Comparison of the measured and predicted natural frequency of corrugated board supporting a steel mass

Load Lb	Measured natural freq. Hz	Predicted natural freq. Hz
20.2	116	115.8
30	114	113.9
40.2	111	111.1

As a result of these test it was determined that the corrugated sheet could be represented in the RoPUL model as a vertical frame element, whose modulus of elasticity is determined from its natural frequency.

4.3 Modeling the pallet component of the unit load

The most common pallet style in use in the US today is a 48" x 40", double faced, non-reversible, flush, three-stringer, partial 4-way (McCurdy and Phelps 1992). The typical stinger style pallet is composed of two types of parts, stringers and deck boards. If the pallet is sitting flat on a surface during transportation, the bottom deck can be ignored as it contributes little, other than horizontal stiffness to the system. Therefore, the two-dimensional model of a three stringer pallet (Figure 2) is composed of a single element representing the top deck, supported by a number of zero-length linear elastic springs representing the contact area and fastener, between the stringer and deck board.

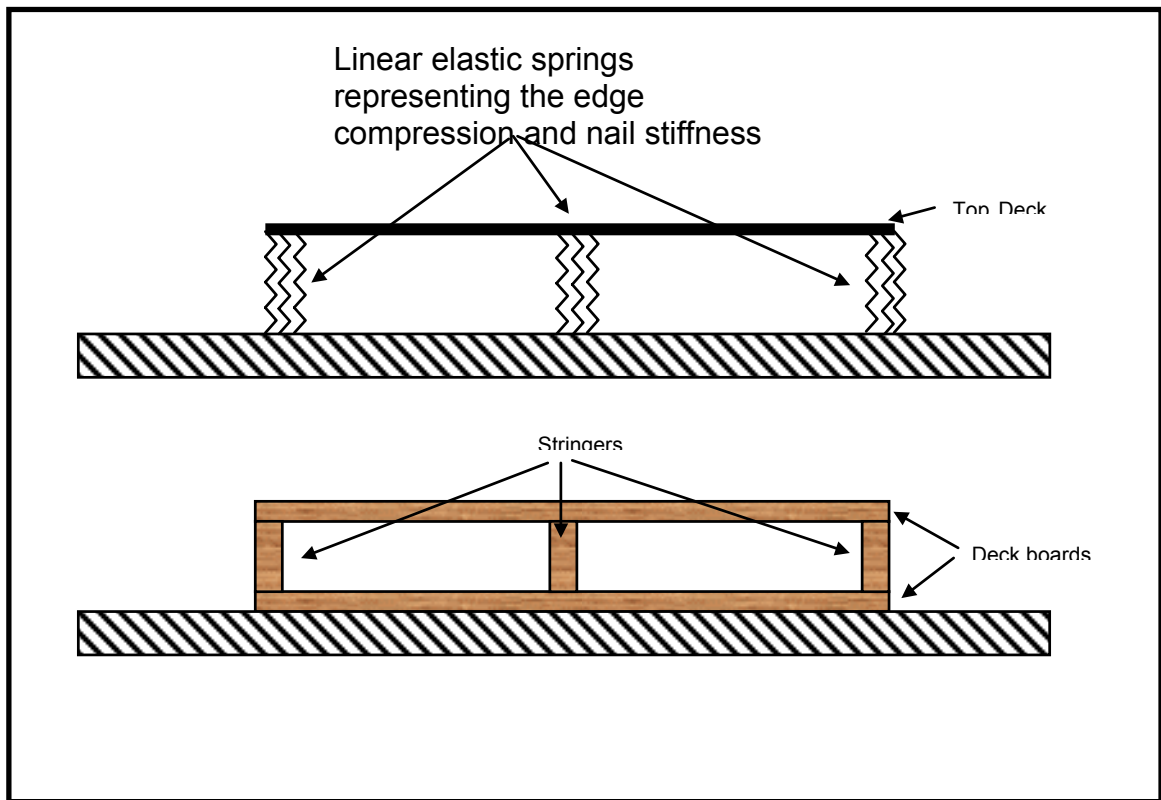


Figure 2. Schematic diagram of 2-d RoPUL model of a stringer pallet.

4.3.1 Modeling a pallet deck board

Wood members in bending, at low levels of deformation respond elastically to applied loads. While it is generally acknowledged that the dynamic stiffness of wood is greater than its static stiffness, the stiffness at the high rate of loading experienced during resonance is not well documented in the literature. Lauer (1991) observed a number of pallet designs during resonance and found them to be vibrating at between 9-13 Hz. at between four and six g's.

To determine the deck board stiffness at high rates of loading a series of bending tests were performed. The details of the testing are found in Appendix A. Test specimens were made from four species commonly used in pallets: Hard maple (*Acer spp.*), Red oak (*Quercus spp.*), Yellow poplar (*Liriodendron tulipifera*), and Southern yellow pine (*Pinus spp.*). Two specimens of each species were tested. Each specimen was simply supported and centrally loaded at deflection rates ranging from 0.01 in/min to the limit of the test equipment 96 in/min. A log linear equation was fit to the resulting data (Figure 3) using least squares regression:

$$E_{rate} = -250000 + 1.165(E_{static}) + 38798(\ln(rate)) \quad (8)$$

E_{rate} = Modulus of Elasticity at loading rate

E_{static} = Modulus of Elasticity at std. loading rate

rate = loading rate ($\frac{in}{min}$)

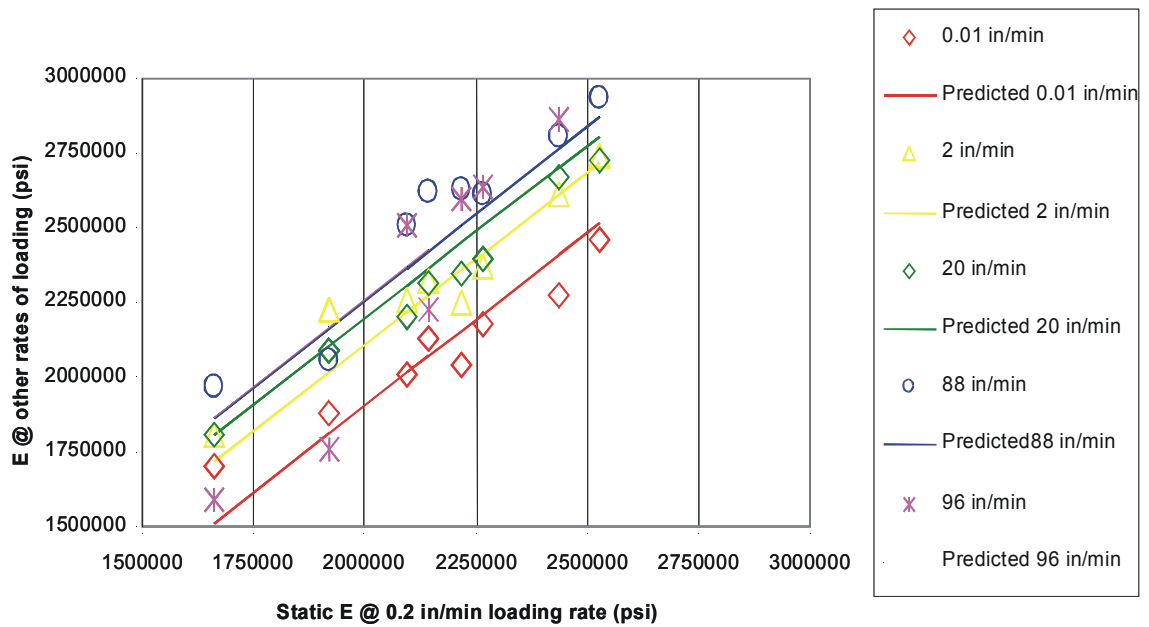


Figure 3. The effect of loading rate on the bending stiffness of the pallet deck-board

By utilizing equation 8 the effective stiffness (E_{rate}) of the deck board can be estimated as a function of the Modulus of Elasticity as measured in a standard bending test (ASTM D-143), and the expected rate of loading.

4.3.2 Modeling the connection between the stringer and the deck board

Samarasinghe (1987) developed a model for predicting the rotational modulus of block style pallet joints. This model idealized a pallet joint as a beam supported by linear elastic springs representing the contribution of the nail shank resistance to withdrawal, nail head embedment resistance, and edge compression stiffness to the overall joint rotational stiffness. Samarasinghe developed regression models for predicting each of these stiffnesses based on joint parameters. In this study both the nail shank withdrawal, and head embedment stiffness models were developed from empirical data, while the edge compression stiffness was developed from derived data developed from simulations of actual joint rotation test. These models were originally developed to predict the static deflection of wooden pallets.

Testing was then done to validate the adequacy of these models for predicting the dynamic behavior of pallets. Details of these tests are found in Appendix B. To validate the head embedment and shank withdrawal stiffness an eight deck-board to stringer joints were constructed from four commonly used hardwoods. Each joints was then tested in axial withdrawal to measure the combined head embedment and shank withdrawal stiffness. The combined nail stiffness was then compared to values calculated using Samarasinghe's equations. Table 3 shows the joint stiffness as measured in these test compared to those predicted by Samarasinghe's model.

Table 3. Estimated and measured pallet joint nail stiffness in tension

Deck-board species	*Estimated K (lb/in)	*Measured K (lb/in)
Southern yellow pine	23600	24200
Hard maple	25200	22900
Yellow poplar	24700	24200
Red oak	29500	23900

* Average of two tests

In general Samarasinghe's equations underestimated the spring constants in these test. However with the exception of the Red oak samples the models did a reasonable job of estimating the spring constants, and these estimates were used for testing the edge compression model. The edge compression model was tested by comparing the center deflection of nailed single span pallet sections to those predicted by a RoPUL simulation using joint spring constants calculated using Samarasinghe's models. The measured and predicted deflections with a 75 lb. load are shown in Table 4.

Table 4. Estimated and measured pallet section center deflection

Deck-board species	Estimated deflection (in)	Measured deflection (in)
Southern yellow pine	0.100	0.087
Hard maple	0.075	0.067
Yellow poplar	0.070	0.055
Red oak	0.088	0.074

A sensitivity study was done on the effect of nail stiffness and edge compression stiffness values on the deflections predicted by RoPUL. As can be seen in

Figure 4, an under-estimation of the nail stiffness would not have had a significant influence on the center deflection of the model.

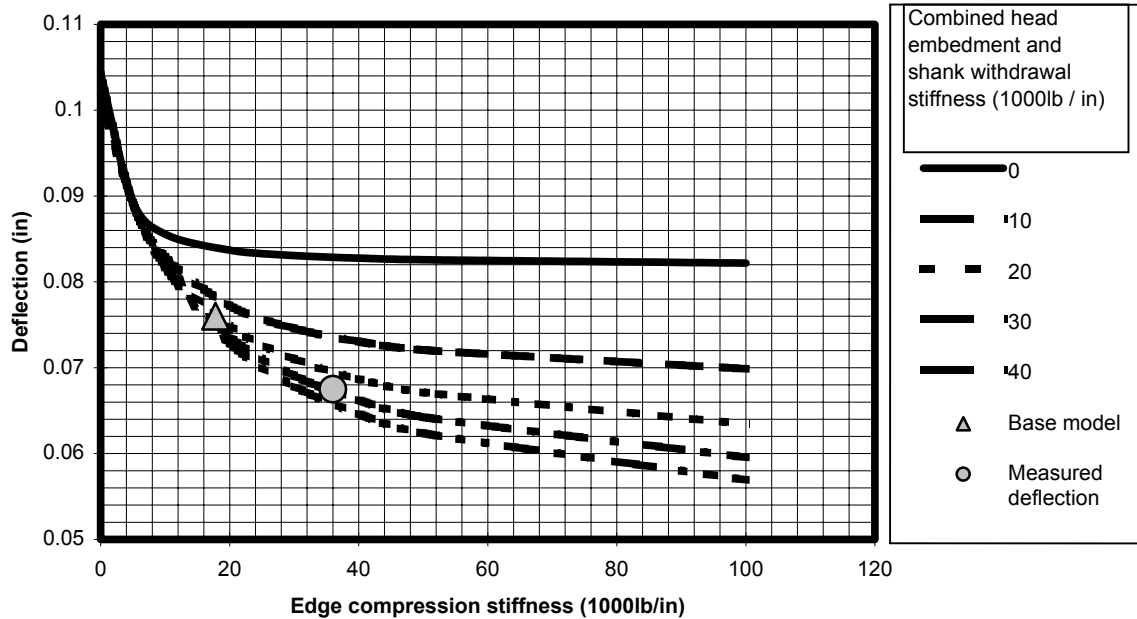


Figure 4. Effect of nail stiffness and edge compression stiffness on the predicted center deflection of a RoPUL model of a single span Hard maple pallet section caused by a 75# load.

However, the edge compression model also developed by Samarasinghe (1987) may not be appropriate for use in the RoPUL model of a stringer pallet. A possible reason for this is that Samarasinghe's model was developed for block style pallets, which have a much larger joint area than the stringer pallets being modeled. In addition Samarasinghe's model was being used to describe large deformations (0.1 inches) of the joint, where as the RoPUL model was being used to describe the minute deformation (0.001 in.) at the joint during deck board

resonance. A new edge compression model was developed based on the elastic properties of the materials involved. In this model each component of the joint is viewed as a spring, thus the joint is composed of three springs in series representing the top deck, the stringer, and the bottom deck (Figure 5). When the deck deflects during vibration, the top deck flexes compressing both the inner and outer edges of the stringer as shown schematically in Figure 6.

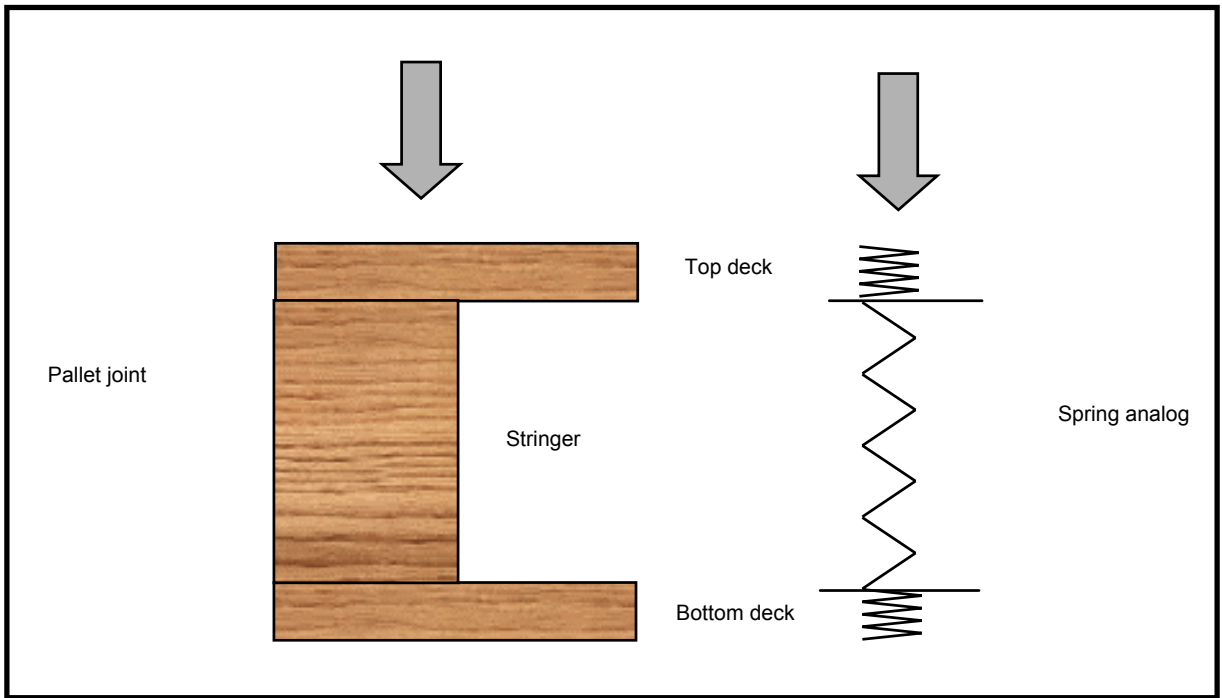


Figure 5. Three components of a pallet joint contributing to the edge compression stiffness of the joint

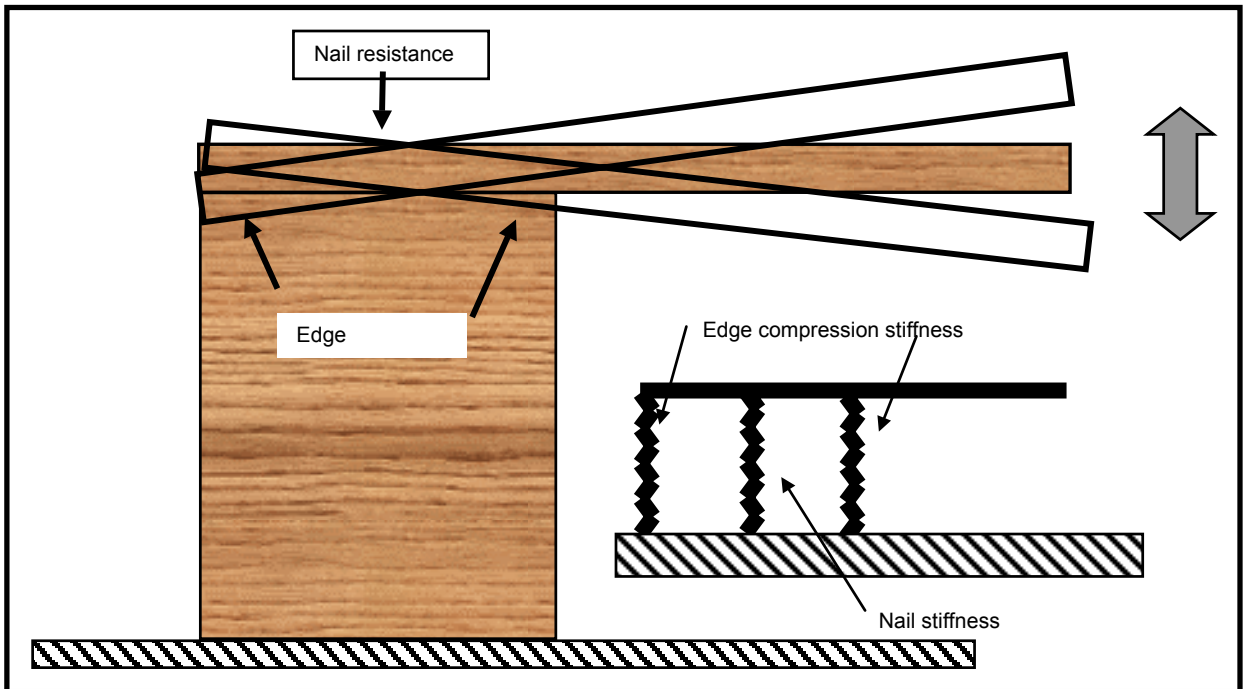


Figure 6. Edge compression during vibration and RoPUL analog deck-board to stringer joint

To determine an equivalent spring constant for the RoPUL model the area being compressed and the elastic properties of each component in the direction they are being loaded was determined. If it is assumed that all the lumber from which the pallet was constructed was flat sawn, we can assume the elastic constants needed are E_{radial} for the deck boards and $E_{\text{tangential}}$ for the stringer. Sliker et al (1994), used compression tests to develop a series of equations for predicting the non-shear elastic constant for a number of hardwood species based on their specific gravity. Given that these equations were developed from compression tests of hardwood specimens loaded at similar levels as would be expected for pallet joints in vibration, this seemed to be an appropriate model. The spring constant for the edge compression component of the joint model can be defined

as shown in equation 9.

$$\frac{1}{K_{ec}} = \frac{1}{K_{td}} + \frac{1}{K_{st}} + \frac{1}{K_{bd}} \quad (9)$$

K_{ec} = edge compression stiffness

K_{td} = top deck stiffness = $E_r(\text{topdeck})$

K_{st} = stringer stiffness = $E_t(\text{stringer})$

K_{bd} = bottom deck stiffness = $E_r(\text{bottomdeck})$

During resonance, the deck board pivots on the stringer as it bends. During each cycle, only a portion of the joint at the edges is compressed. The contribution to the total joint resistance to bending, of the wood being compressed, is a function of the wood stiffness, and the area being compressed. To determine the effective edge compression area, simulations were performed using the pallet deck model. The general model was modified to divide the joint area into 1/10-inch sections each supported by a spring, representing the stiffness of the wood below it. For the downward cycle (Figure 7), the simulation is conducted with the expected load, and the static deflection of the deck is determined for all nodes in the joint area. If during the simulation the node exhibits a positive deflection, that is to say, its deflection is away from the joint; in the next simulation those springs are removed. The process continued until only those springs that are compressed when the deck is loaded remained. To determine the edge compression area for the upward cycle (Figure 7) the process is repeated with the loading in the opposite direction.

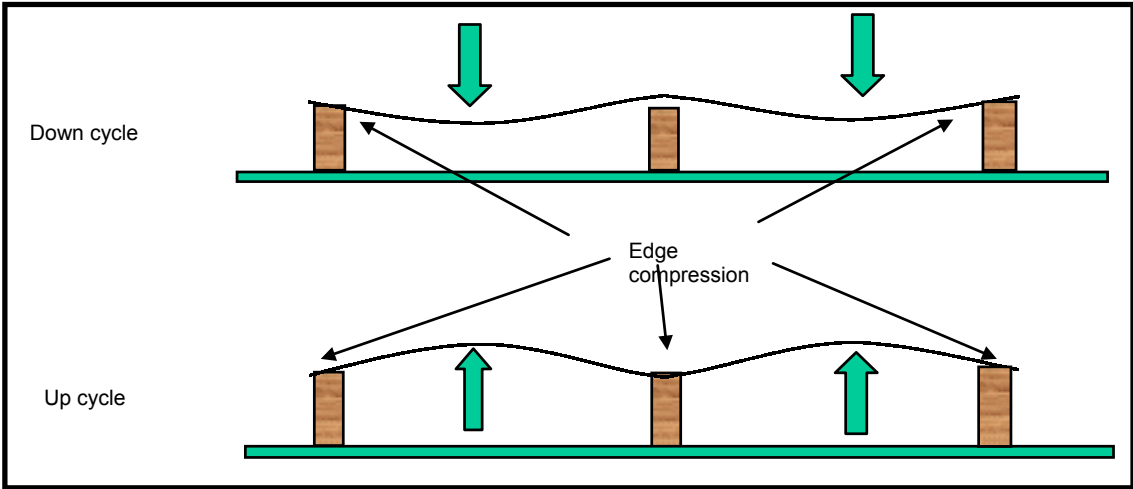


Figure 7. Schematic diagram of the location of edge compression during cyclic loading

The new model for estimating edge compression stiffness was similarly tested using a second set of single span pallet sections. As can be seen in Figure 8 the center span deflection estimated by RoPUL are much closer to the measured deflections than with the previous edge compression model.

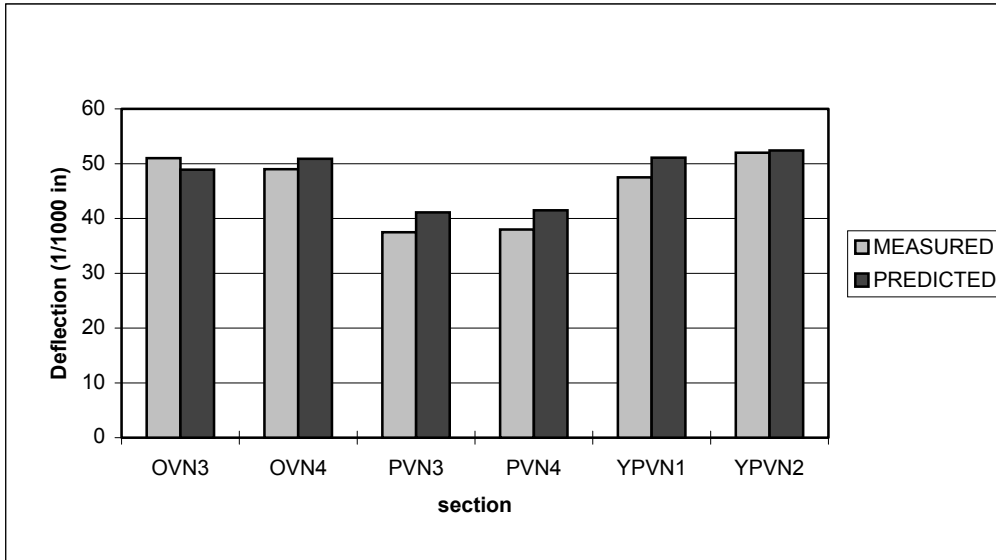


Figure 8. Center span deflections estimated using new edge compression stiffness model

4.3.3 The combined model

The typical unit load is comprised of a single pallet, but may contain numerous layers of containers and products. With only minor modifications the model of the pallet described above can be modified to represent a number of common configurations. One way to give the same flexibility to the containers and load was to simplify their representation within the finite element model. Using a single component model to represent a single layer of the load over each

of the spans in the three-stringer pallet analog, allows the model to represent many types of loads without having to change the geometrical representation of the model.

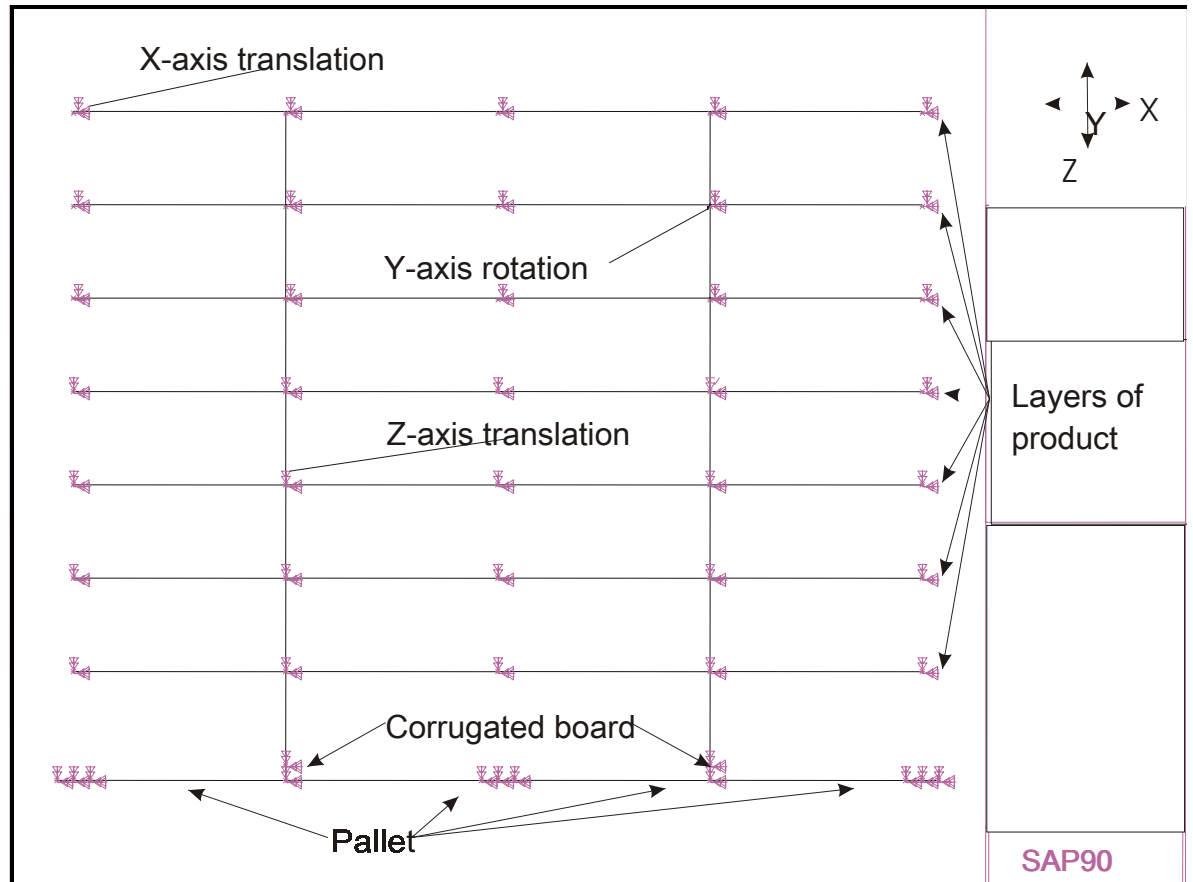


Figure 9. Wire frame diagram of the combined model showing restraints at each node

As can be seen in Figure 9 the only restraint placed on the RoPUL model nodes are restraints on out of plane motion. In this case the RoPUL is restrained from moving along the y-axis and from rotating around the x-axis and z-axis. This leaves the model free to move vertically and horizontally within the x-z plane and to rotate about the y-axis, which allows rotation in the x-z plane. The only other

constraint placed on the model is the need for the placement of springs to provide some resistance in the x-direction to resist horizontal motion of the frame due to vertical loading. This provides the needed stability to the structure to allow for the use finite element analysis of the structures behavior. The location of the springs is shown in Figure 10.

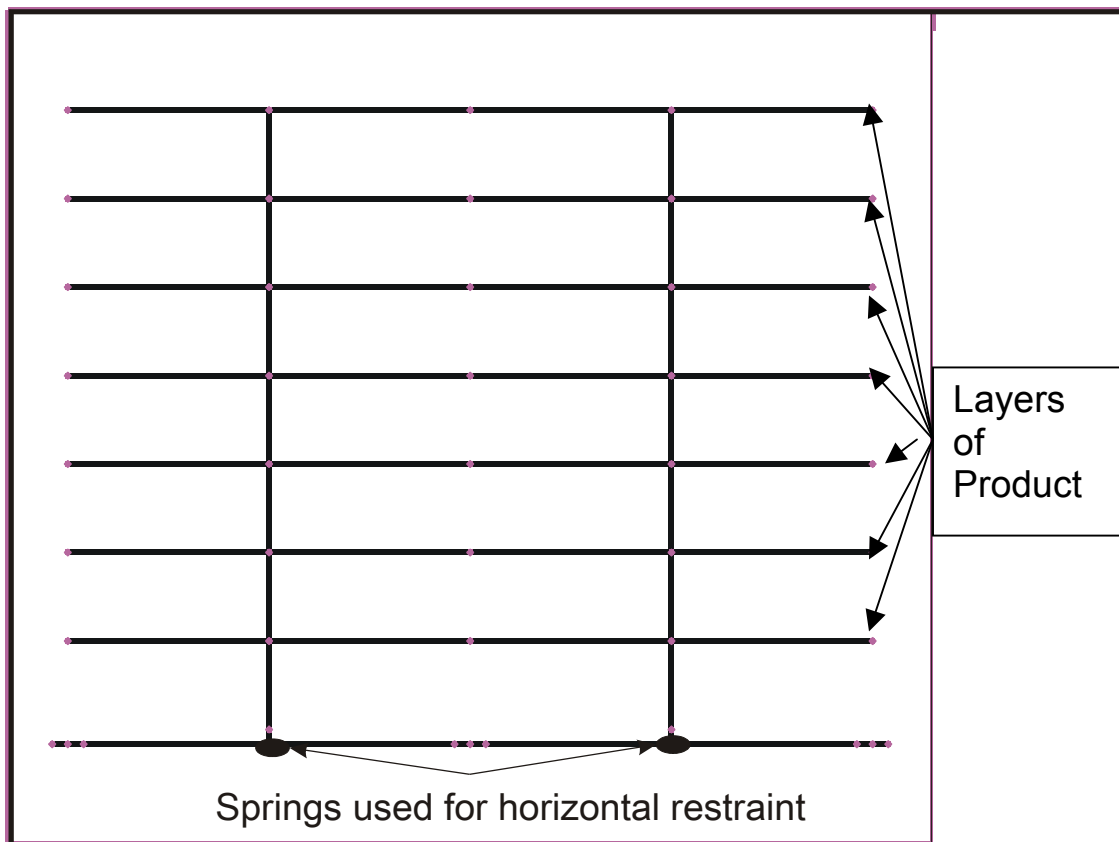


Figure 10. Location of horizontal restraining springs

It was determined from trial runs of the model that the minimum stiffness of the horizontal springs necessary to stabilize the structure was 100 lbs/in. The springs were placed at the center span of the frame representing the pallet deck where they would act to provide a stable base for the rest of the model, much as

a pallet provides a stable base for its load. Horizontal springs of this magnitude do not appear to influence the vertical resonant frequencies of the combined model.

Within the SAP90 framework the load carried by a column element is transferred through the central axis of the column to the beam element below it, regardless of the true dimension of the column. In using a single column to represent the sheet of corrugated spanning the deck of the pallet in the RoPUL model this causes the model to behave as if the pallet deck is supporting a point load at the central axis of the column rather than the actual uniformly distributed load being transferred through the corrugated to the pallet deck. One way to solve this problem would be to modify the model by adding elements to represent the load. The more elements added the more the model would behave as if it were supporting a uniformly distributed load. However the model would become very cumbersome to use. Another approach, the one chosen, would be to adjust the mass supported by the column to cause the deck to behave as if it was supporting a uniformly distributed load. The key to this approach is being able to adjust the mass to create an equivalent bending moment (for a uniform load and a point load) at the center to the deck board span. The advantage of this approach is that a number of mass conversion factors could be easily developed for a number of standard loading configurations. By equating maximum moments, the equivalent center loaded mass for a uniformly distributed load can be calculated.

$$\frac{P_u L}{8} = \frac{P_c L}{4} \quad (10)$$

P_u = total load for uniformly loaded beam

L = length

P_c = load for center loaded beam

Solving for the concentrated center load, we have:

$$P_c = \frac{P_u}{2} \quad (11)$$

The equivalent load on a center-loaded beam would have to be only half as large as the load on a uniformly distributed beam to create the same maximum bending moment. To determine the effect this simplification would have on the behavior of the SAP-90 model, simulations were conducted of a simply supported beam. The first with a uniformly distributed mass, the second with the mass concentrated in the center of the beam, and the third with the mass concentrated at the center of the beam. Each beam had identical geometry but the mass of the elements making up the beam were adjusted to yield the same maximum bending moment (Figure 11).

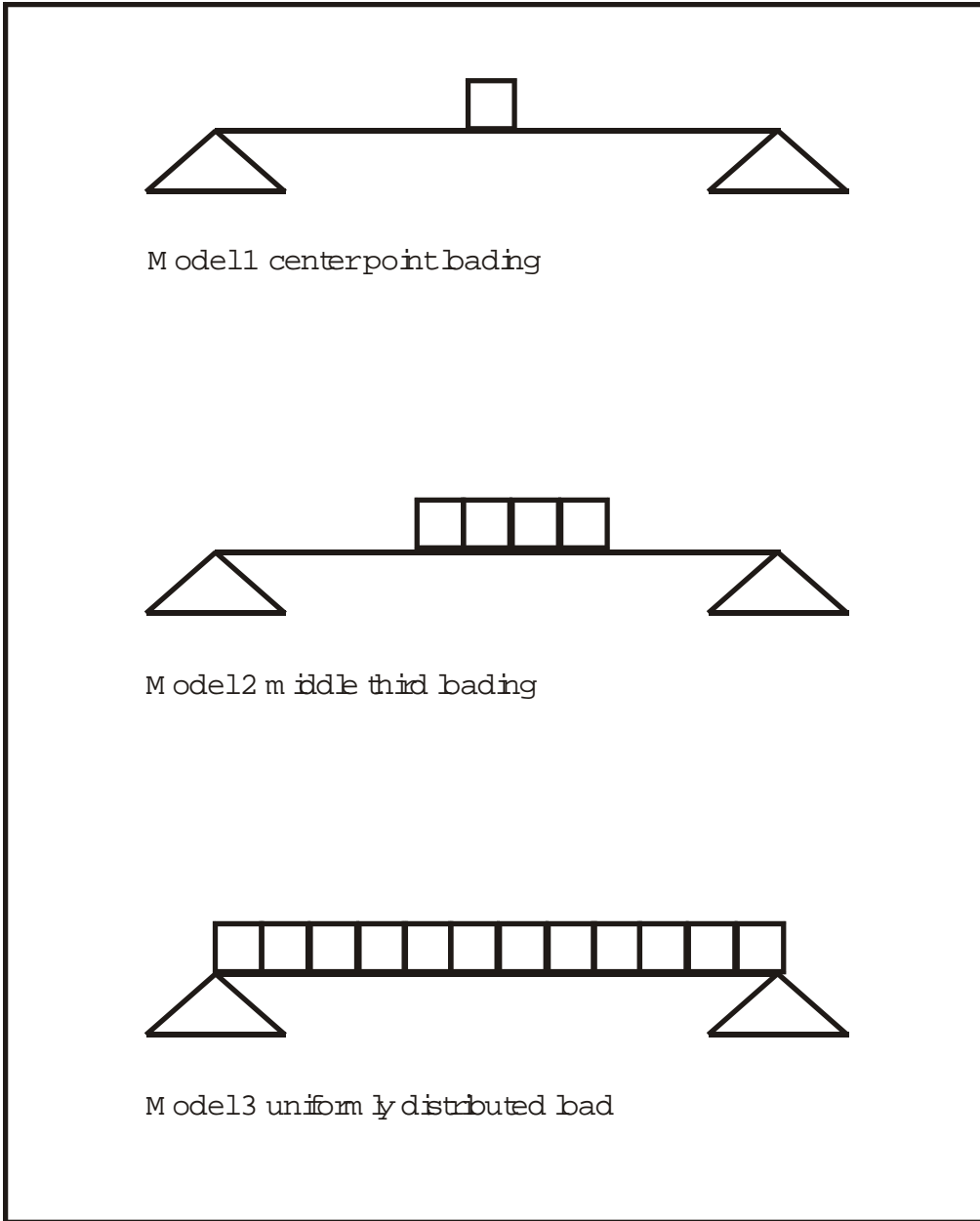


Figure 11. Simply supported beam models for bending moment testing

The SAP90 input files for the three models can be found in Appendix E. All three models are identical with the exception of the weight and mass of the frame elements forming the loaded section of the beam. The weight and mass per linear inch for these sections was calculated to provide the needed total load to

produce equivalent bending moments in each model. Table 5 summarizes these differences.

Table 5. Summary of bending moment model results

Model	Total load (Lbs)	Natural frequency (Hz)
Center	133.33	18.7
Middle third	160	18.27
Uniformly distrib.	267	19.05

Because the most likely conversion to be used with bulk loads is from a uniformly distributed load to a center load, it was decided the error introduced into the RoPUL model using this conversion was acceptable.

5.0 Validation of the unit load model

To validate RoPUL two different full size loads of a vibration sensitive product was tested. The first test load (test one) consisted of a yellow-poplar (*Liriodendron tulipifera*) pallet supporting a triple wall corrugated bulk bin filled with approximately 900 pounds of apples (Figure 12). This selection provides a fairly simple example of a unit load while allowing for interaction to occur between all three components: the product, the container, and the pallet.



Figure 12. Test 1 unit load used in the validation testing of the RoPUL model.

The second test load (test two) consisted of a yellow-poplar (*Liriodendron tulipifera*) pallet supporting a double wall corrugated bulk bin filled with approximately 500 pounds of peaches (Figure 13).



Figure 13. Test 2 unit load used in the validation testing of the RoPUL model.

5.1 Simulating a piece of fruit using a finite element product analog

The products chosen for the validation tests were a red delicious apple, and a peach. The choice was driven mainly by the availability of ripe fruit at the time of testing, and the sensitivity of both fruits to vibration induced damage. The apples used in the validation tests were picked and then placed in cold storage to

prevent ripening until they were used for testing. All measurements on the peaches were made on the day of the test because of the ripe condition the fruit was in when picked.

The physical properties (size and mass) needed for the RoPUL model were determined from a random sampling of the fruit used in the validation test. During harvesting, an attempt was made to select fruit of a uniform size. From the apples harvested a random sample of 20 apples were selected. Each apple was then marked for identification. The diameter and weight of each apple was then measured, and the apples were returned to storage. The apples ranged in weight from 0.48 to 0.65 pounds with an average weight of 0.56 pounds. The average apple diameter was 3.5 inches. Statistical analysis of the measurement was done to determine the sample size necessary to produce a 95% assurance that the mean measurement was within 5% of the actual mean. Because of the uniform condition of the apples only six measurements were necessary to reach the selected level of accuracy. Prior to testing the apples were again weighed to determine if there had been any change in the apple's weight during storage. No weight changes were observed during storage and as a result, the average size and weight originally measured were used for the simulation.

Since it was not possible to acquire a large quantity of uniform peaches for the test a larger initial sample was taken to determine the material properties needed for input into the RoPUL model. From the peaches harvested a random sample of 100 apples were selected. Each peach was then marked for identification. The diameter and weight of each peach was then measured, and

the peaches were returned to storage. The peaches ranged in weight from 0.24 to 0.72 pounds with an average weight of 0.47 pounds. The average peach diameter was 3.0 inches. Statistical analysis of the measurement was done to determine the sample size necessary to produce a 95% assurance that the mean measurement was within 5% of the actual mean. A sample of 34 peaches was necessary to reach the proposed level of accuracy.

To determine the mechanical properties it was necessary to determine the natural frequency of the fruit. Three of the twenty apples selected earlier were tested to determine their natural frequency. A piezo-electric accelerometer was affixed to the top of an apple with double-faced carpet tape. The apple was then subjected to a series of sine sweep vibration tests in accordance with ASTM D-999. The natural frequency was determined from the acceleration vs. frequency plot. The natural frequency of the apples varied from 63 to 73 hertz; and averaged 68 hertz. Using equation 7 the effective stiffness of the column representing the apple was calculated. The effective stiffness was then entered into the model as the column's modulus of elasticity.

Thirty-five of the 100 peaches selected earlier were tested to determine their natural frequency. A piezo-electric accelerometer was affixed to the top of a peach with double-faced carpet tape (Figure 14). The peach was then subjected to a series of sine sweep vibration tests in accordance with ASTM D-999. The natural frequency was determined from the acceleration vs. frequency plot. The natural frequency of the peaches varied from 29 to 85 hertz; and averaged 52.8 hertz. Using equation 7 the effective stiffness of the column representing the

peach was calculated. The effective stiffness was then entered into the model as the column's modulus of elasticity.

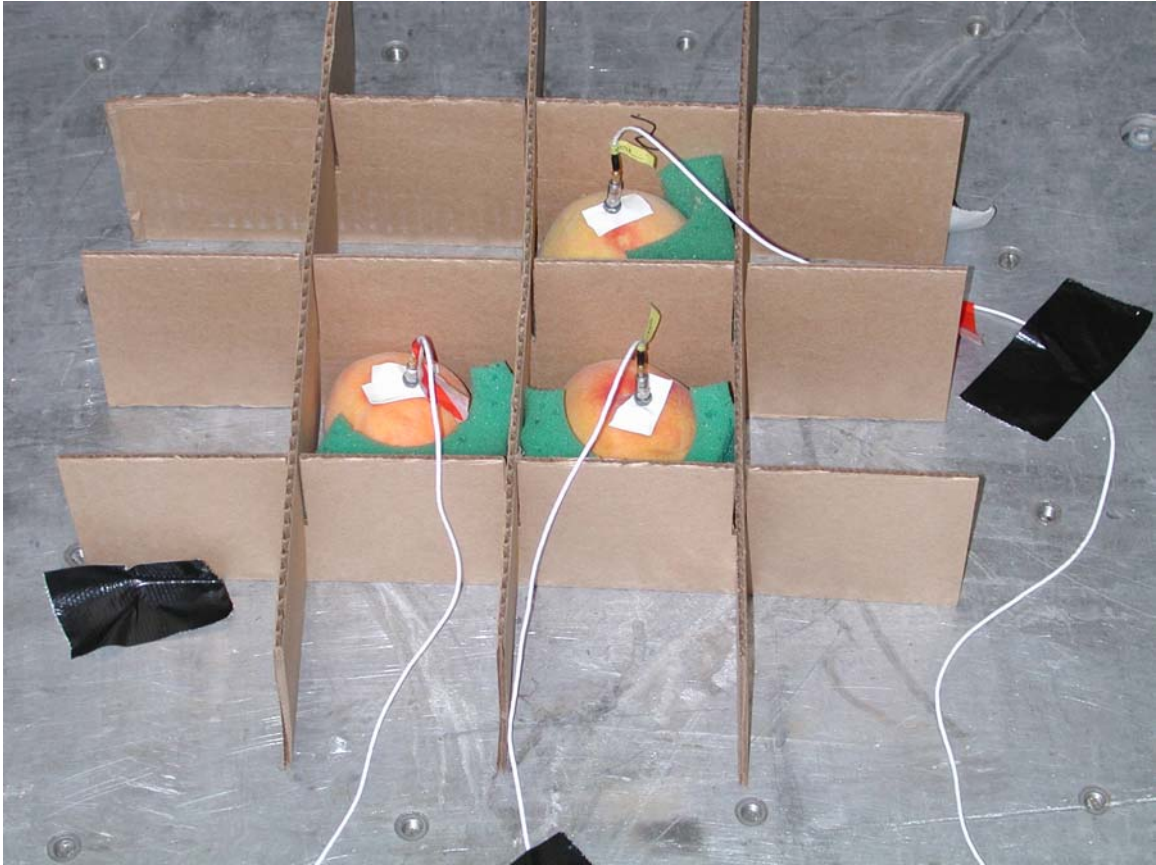


Figure 14. Vibration test of individual peaches to determine their natural frequency

5.2 Test container stiffness

Like the product, the corrugated board is modeled as a column supporting the product. Consequently, it is necessary to determine an effective stiffness

value for that column, along with the physical characteristics of size and mass. To determine the effective stiffness of the corrugated board used in the model validation test, it was first necessary to calculate the load that it would be supporting.

The total weight of apples used in the test was 900 pounds. The dimensions of the bin used were 47 inches long, 41 inches wide and 40 inches tall. This corresponded to a loading of 0.47 pounds per square inch. The effective stiffness of the corrugated board was then determined in a similar manner as the stiffness of the product. In this case a vibration test of a section of the bottom of the corrugated bin supporting a steel plate providing an equivalent loading of 0.47 pounds per square inch. The natural frequency of the loaded corrugated board was in turn used to calculate the effective stiffness of the column using equation 7.

With the peach test load, vibration tests were performed on each layer as the peaches were loaded. Thus it was necessary to calculate the board stiffness at each load level. Each layer of peaches weighed approximately 85 lbs. The interior dimensions of the bin used were 40 inches x 40 inches. This corresponds to a loading of 0.053 psi per layer. Tests were conducted on samples of corrugated loaded with steel plates at loading of 0.053 psi, 0.106 psi, 0.159 psi, 0.265 psi, and 0.318 psi corresponding to 1, 2, 3, 4, and 5 layer respectively. The natural frequency of the loaded corrugated board was in turn used to calculate the effective stiffness of the column using equation 7.

5.3 Pallet model validation

The pallet used for test one in the full-scale validation test was manufactured from a single yellow-poplar (*Liriodendron tulipifera*) log. The green lumber was cut into rough blanks and then sealed in plastic and placed in cold storage to maintain its moisture content. During the production of the rough blanks samples were cut from each board for use in determining the lumbers moisture content and specific gravity. Control blocks were also fashioned from each blank, weighed and stored with the machined blanks to monitor any moisture content changes during storage. The rough blanks were removed from cold storage one at a time and machined to their final dimensions. After machining, the blanks were again wrapped and returned to storage. The modulus of elasticity of each piece was then determined using a third-point-bending test. The average modulus of elasticity for all the deck boards was then used as a basis for the calculation of the effective stiffness of the deck boards. Past tests of loads of apples (Peleg and Hinga 1986) has shown an expected output acceleration of 2 g's. This was used as a basis of the expected loading rate of the pallet deck for calculation of the decks effective stiffness. Using Samarasinghe's (1987) model, nail stiffness values, and Sliker et al's (1994) equations, the model edge compression stiffness values were calculated from the pallet lumber specific gravity values determined earlier.

The pallet used for test two in the full-scale validation test was manufactured from kiln dried fully surfaced yellow-poplar (*Liriodendron tulipifera*) lumber. During the production of the deck-boards samples were cut from each

board for use in determining the lumbers moisture content and specific gravity. Control blocks were also fashioned from each blank, weighed and stored with the deck-boards to monitor any moisture content changes during storage. The modulus of elasticity of each piece was then determined using a third-point-bending test. The average modulus of elasticity for all the deck boards was then used as a basis for the calculation of the effective stiffness of the deck boards. It was assumed that the peaches would encounter similar acceleration levels as those experienced by the apples. This was used as a basis of the expected loading rate of the pallet deck for calculation of the decks effective stiffness. Using Samarasinghe's (1987) model, nail stiffness values, and Sliker et al's (1994) equations, the model edge compression stiffness values were calculated from the pallet lumber specific gravity values determined earlier.

Validation tests were performed on pallet sections built to simulate the behavior of full size pallets. Tests were conducted on a pallet sections loaded with a sheet of corrugated supporting a steel mass. It was assumed that the corrugated board was flexible enough to provide a uniformly distributed load despite the rigidity of the load and the natural and induced variation in the surface of the pallet deck. To check this assumption a RoPUL model of a simply supported steel plate was created (Appendix F). From this simulation it was determined that the natural frequency of the plate used in the pallet section test was about 4500 Hz, well above those observed during the pallet section test. Pallet section model predictions show good agreement with actual test results.

Table 6. Results of section test with steel plates supported by C-flute corrugated.

Section	RoPUL prediction	Vibration test result
Oak deck, C-flute, 20#mass first mode	28 hertz	30 hertz
Oak deck, C-flute, 20# mass second mode	48 hertz	46 hertz
Oak deck, C-flute, 40#mass first mode	20 hertz	22 hertz
Oak deck, C-flute, 40# mass second mode	34 hertz	34 hertz

5.4 Validation of the RoPUL model of a unit load

5.4.1 Introduction

Two different unit loads were tested during the validation process. Both were palletized bulk bins containing fresh fruit. The difference in the two tests is summarized in Table 7.

Table 7. Summary of characteristics of unit loads used in the validation test

Component	Characteristic	Test 1	Test 2
Product			
	Type	Apples	Peaches
	Diameter	3.5 in	3.0 in
	Weight	0.79 lb	0.47 lb
	Natural frequency	67 Hz	53 Hz
	MOE	120.87 psi	44.9 psi
Container			
	Wall construction	Triple wall	Double wall
Pallet			
	Size	48 in x 40 in	40 in x 40 in
	Deck material	Yellow-poplar	Yellow-poplar
	Deck thickness	0.6875 in	0.75 in
	Stringer material	Yellow-poplar	SPF 2x4
	Moisture content	40 %	12 %

During test number one only a single loading configuration was evaluated. This was a fully loaded bin containing approximately 900 pounds of apples. During the second round of testing, test two, each layer was tested as the bin was loaded.

5.4.2 Test 1 apples

The design for the test pallet #1 is shown in Figure 15. The pallet was hand nailed using a high quality helically threaded harden steel nail. All nails were slightly counter sunk to assure good contact between the nail head and the deck board. After assembly the pallet was weighed wrapped in plastic and returned to storage to minimize moisture content change prior to testing.

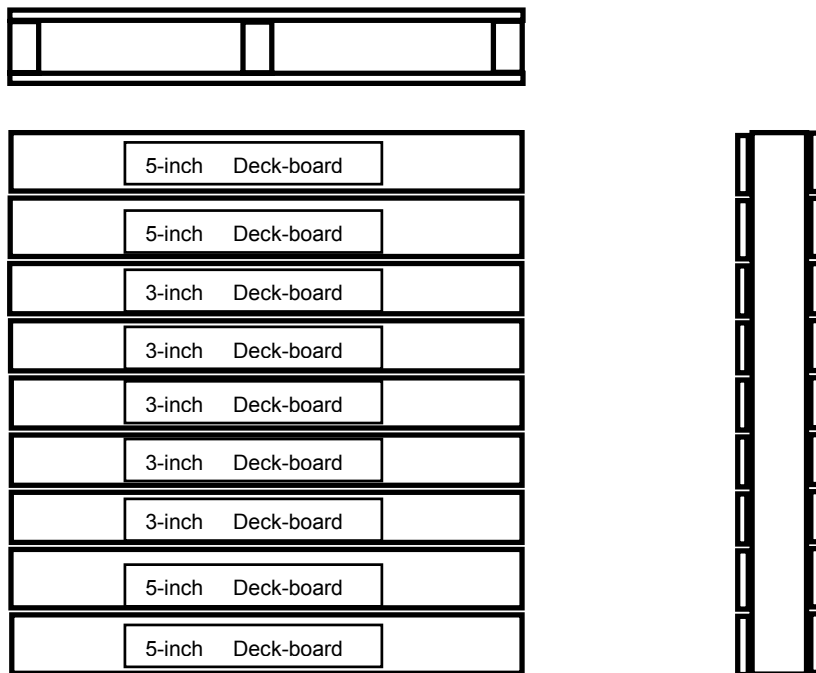


Figure 15. Schematic of test 1 pallet

The corrugated bin used in the validation test 1 was constructed of 900 # burst test, triple wall corrugated board. The bin had a preformed manufactures joint, and the bottom closure was sealed with duct tape. The bin was then placed on the pallet for filling with apples.

Due to availability at the time of testing the apple load used was composed of two varieties of apples. Approximately 600 lbs. of the load was made from green harvested Cortland apples. The other 300 lbs. was composed of fresh harvested ripe red delicious apples. To insure accurate measurement of the vertical resonance of a particular variety of apples, the apples were carefully placed in the bin one layer at a time, to create columns of the same variety apples. The bin was loaded to a depth of 36 inches (approximately 7 layers of apples). All test measurements were made with an accelerometer mounted on top of a column of red delicious apples (Figure16). All material properties for the apple load used in the RoPUL model were taken from measurement of a sample selected randomly from the red delicious apples.

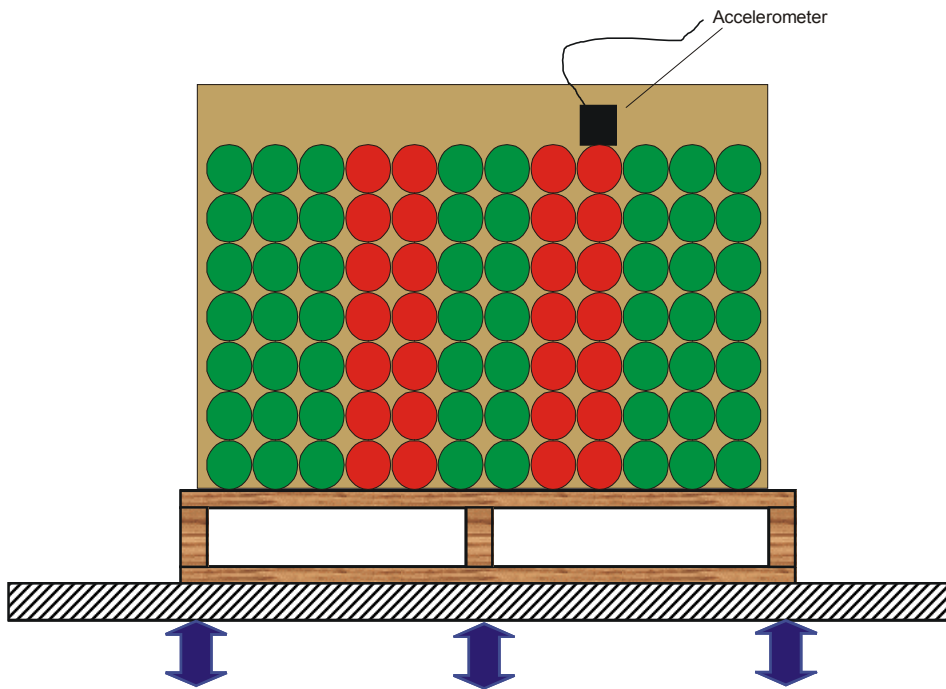


Figure 16. Apple placement and location of accelerometer during unit load vibration test.

The pallet with the loaded bin was then placed on the vibration table (Figure17). The instrumented apple was loosely attached to three of the apples adjacent to it with duct tape. This was necessary to prevent instrumented apples from rotating during the subsequent vibration tests. The unit load was then subjected to a sine-sweep vibration test, ranging from 5 hertz to 100 hertz, at 0.33 g's of input acceleration, which prior test had shown would produce a peak output acceleration of approximately 2 g's. The test was repeated with apples at other locations in the bin (Figure18).



Figure 17. Vibration test set-up for unit load validation test

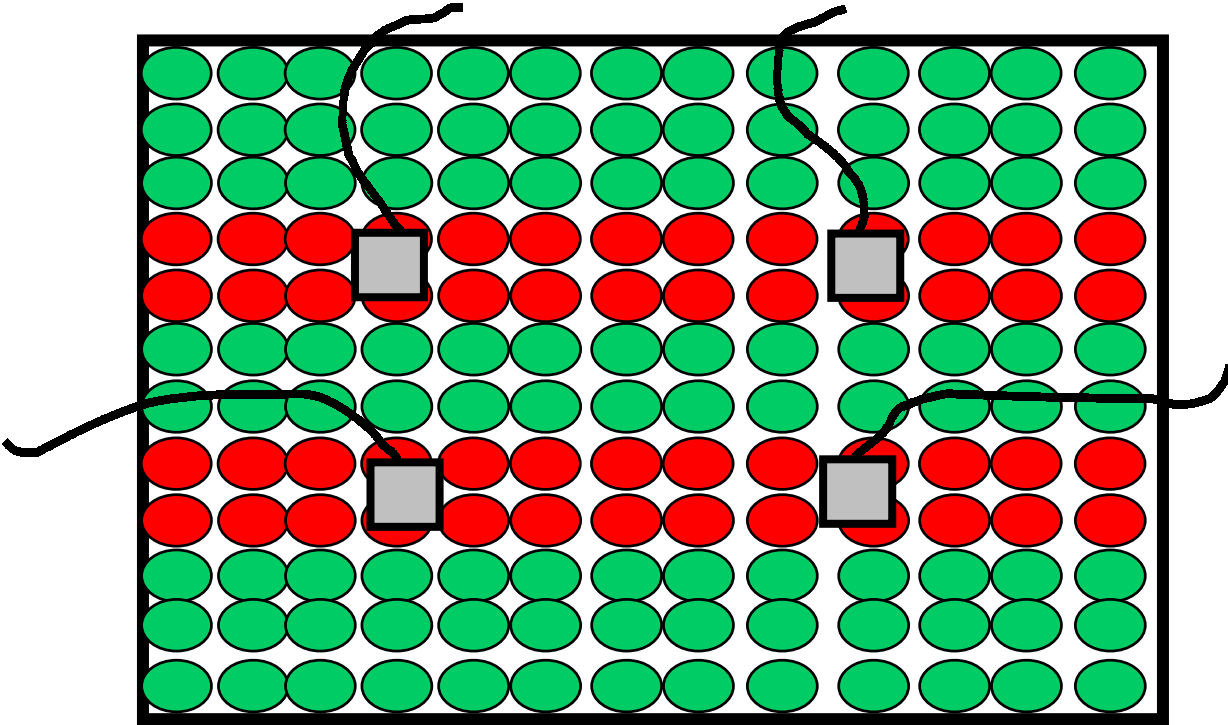


Figure 18. Accelerometer placement for Unit load test 1

Figure 19 is a typical output response plot of the acceleration as a function of frequency. Peak accelerations (resonance) occurred at 10-15 hertz and at 40-45 hertz. The model simulation of the unit load predicted two major vertical resonance's one at 13.6 hertz and another at 41.3 hertz.

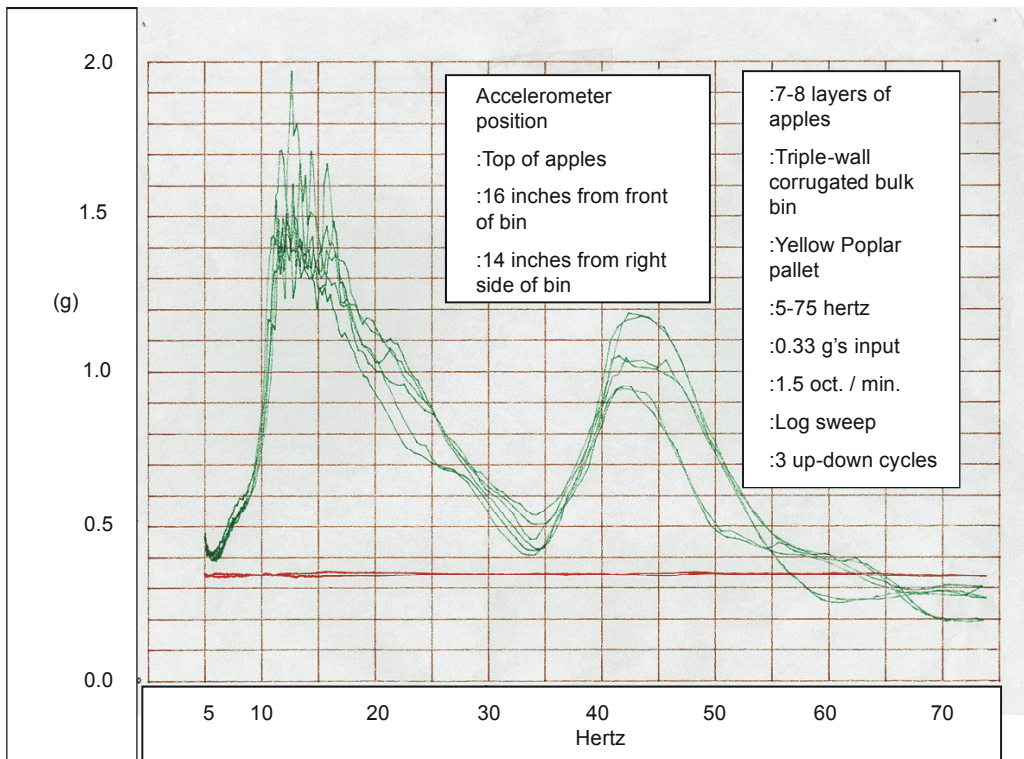


Figure 19. Typical Unit Load Vibration test output for test 1

5.4.3 Test 2 peaches

Pallet for test 2 was of a similar design to that of test 1, with Seven evenly spaced 5.5-inch deck-board forming the top deck (Figure 20). It was constructed with the same nail used for pallet 1. The bin for test two was a constructed of a 600 lb burst test double wall corrugated board.



Figure 20. Test 2 pallet

Due to availability at the time of testing the peach load used was composed of several varieties of peaches. The bulk bin was positioned on the pallet to minimize overhang. The peaches were placed in the bin one layer at a time. At the completion of each layer an accelerometer was attached to the top layer of peaches to measure the output acceleration during the vibration test. The instrumented peaches were loosely attached to three of the peaches adjacent to it with duct tape. This was necessary to prevent instrumented

peaches from rotating during the subsequent vibration tests. Each layer in turn was subjected to a sine-sweep vibration test, ranging from 5 hertz to 300 hertz, at 0.5 g's of input acceleration. After the completion of each vibration test an additional layer of peaches was added to the bin and the process was repeated. The instrumented peaches were placed in the same location for each test (Figure LL). A total of five layers of peaches were tested.



Figure LL. Accelerometer placement for Unit load test 2

closely tracked the actual performance of the unit load. The results ranged from a 1.8% underestimation of by the three layers RoPUL model to a 19.3% overestimation by the four layer RoPUL model.

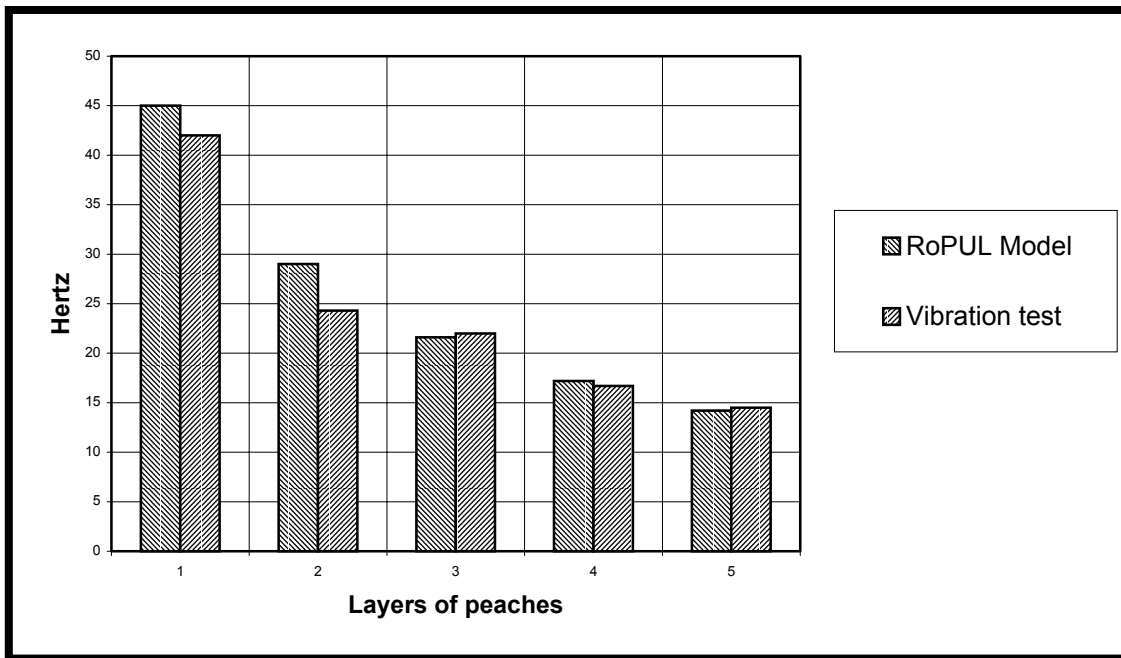


Figure 22. Comparison of RoPUL simulation results to the vibration test results for Test 2 bulk bin of peaches (first vertical mode of resonance)

6.0. A practical application of the RoPUL model

The unit load of apples tested exhibited its first resonance at 13.6 hertz. It has been determined that the primary forcing frequencies found truck transport are between 5 and 20 hertz, with the maximum accelerations found around 10 to 15 hertz (O'Brien et al 1965). It is likely that this unit load would resonate during

truck transport, and the resulting amplification of would cause damage to the load. Using RoPUL, it is possible to design a load that will not resonate during transport. In this unit load, the stiffness of the pallet, the stiffness of the corrugated bin, or the weight of the apple load can be adjusted to change the natural frequency. One can try to increase the natural frequency of the load, beyond that of the expected forcing frequencies, by increasing the stiffness of the pallet or the corrugated bin, or by decreasing the weight of the load. Similarly one can decrease the natural frequency of the load by decreasing the stiffness of the pallet or corrugated bin, or by increasing the weight of the load. Changing the stiffness of the pallet by adjusting the thickness of the deck boards within the range of commonly used ($3/8''$ to $1''$), did not shift the frequency out of the danger range. Decreasing the thickness of the deck from $11/16''$ to $3/8''$ lowered the natural frequency to 10.6 hertz, while increasing the thickness to $1''$ increased it to only 14.4 hertz. Changing the stiffness of the corrugated bin had even less of an effect. Changes in the weight of the load however, did have a major effect on the loads natural frequency. Adding 4 layers of apples (approximately 400 lbs.), shifted the natural frequency down to 11.3 hertz, while subtracting the same amount raised the natural frequency to 21.2 hertz, outside of the expected forcing frequencies found in truck transport. One can further modify the new safer 500 lb load of apples by using a thinner deck ($3/8''$). This change decreased the pallet's stiffness, which drops the natural frequency down to 17.2 hertz, still in the safe region.

For every product there are an infinite number of ways that a unit load can be constructed. Computer models such as RoPUL give packaging engineers a tool for evaluating numerous configurations without the cost of constructing and testing actual loads. As can be seen in the example above, to obtain the desired level of protection within a unit load it is often necessary to modify more than one of its components. Computer simulations such as RoPUL may never completely replace shipment test for evaluating packaging options, but they can be used to develop designs that have a good chance of providing the need level of protection.

7.0 Summary and Conclusion

The objectives of this dissertation have been met. RoPUL is a finite element model that was developed to simulate the dynamic behavior of a unit load consisting of a wooden pallet and a corrugated bulk bin containing a load of fruit. Vibration tests of two different unit load validate that RoPUL can be used to predict the frequencies at which a unit load will resonate. While the present model is limited by its ability to only analyze loads consisting of a single layer of containers, RoPUL provides a tool for investigating the effects that individual components of a unit load have on its dynamic behavior. Simulations such as RoPUL can be used to aid in the design of unit loads that more efficiently protect products from vibration damage.

The individual components of the unit load, the product, the bulk bin, and the pallet were first modeled and validated independently prior to being

assembled in the final RoPUL model. The product model consists of two components, one representing the elastic properties of the product and the other representing the mass of the product. In the RoPUL model the elastic component is represented with a column element that is relatively mass-less, and the mass is represented by an extremely rigid beam element supported by the elastic component column. Given that the product in a bulk bin is self supporting and typically would comprise the majority of the mass of the unit load, it is not surprising that in the case of the bulk bins studied in this project the product by far had the largest influence on the natural frequency of the unit load. As a result the accurate depiction of the behavior of the product is critical to the overall accuracy of the RoPUL model. Breaking the product model into two components allows the dynamic behavior of the product to be easily described mathematically. Once the natural frequency of the product is known, the effective stiffness of the column element needed for the RoPUL model is easily determined.

The bulk bin component of the RoPUL model is represented by a column element supporting each column of the product model. In the RoPUL model of a bulk bin unit load the single layer of corrugated board between the pallet and the product did not appear to play a major role in the overall behavior of the unit load. While it was found that because of the non-linear elastic properties of the corrugated board, that changes in the load being supported by the corrugated board can significantly change its elastic properties, changes in the material properties of this single element in the RoPUL model had only a minor effect on

the overall dynamic behavior of the unit load. However if the model is extended to model multiple layers of containers it is likely that the behavior of the container component of the model will play a more significant role in the dynamic behavior of the unit load. Determination of the materials effective stiffness from vibration tests as was done in this study may provide a method for better understanding the behavior of stacked corrugated container.

The pallet, while not influencing the behavior of the unit load to the same extent as the product did play a large enough role that its construction cannot be ignored. Unlike many wood structures pallets are often subjected to sustained periods of dynamic loading. A better understanding of how the pallets components behave at high rates of loading was necessary. It was found that as the rate of loading increases the modulus of elasticity of the wooden components of the pallet also increased. A logarithmic relationship was develop for describing this behavior, which can be used to estimate the elastic properties of pallet deck-board at the high rates of loading experienced during resonance. The elastic behavior of the deck-board to stringer joint, also had a significant impact on the dynamic behavior of the pallet model. The elastic behavior of the joint is represented in RoPUL by linear elastic springs representing the contribution of the nail shank resistance to withdrawal, nail head embedment resistance, and edge compression stiffness to the overall joint rotational stiffness. A new model based on the elastic properties of the wooden components of the joint was developed to estimate the edge compression stiffness.

Most other models of unit loads have ignored the impact of pallet design on dynamic behavior. The inclusion of the pallet in the RoPUL model will give packaging engineers a new tool for designing efficient unit loads.

8.0 Future Research

The current model, is limited to simulating the behavior of unit loads composed of a single layer of containers, the bottom layer in a stack of containers, or bulk bins. No attempt was made to simulate the complex interaction between stacked containers. Little is known about the effect stacking patterns on the transmission of loads through a unit load, and less about their effect on the dynamic behavior of unit loads. Further research is needed on the behavior of multiple layers of corrugated containers in order to allow this work to be extended beyond bulk containers.

Most products shipped in corrugated containers support or have internal packaging which supports part of the weight of the container stacked above it. Further work needs to be done on the interactions between the components within a corrugated container and how they impact the dynamic behavior of a stack of containers.

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Appendices

Appendix A: Estimation of the effective stiffness of the pallet deck-board.

A 1.0 Introduction

For the RoPUL model to accurately predict the natural frequencies of a unit load the elastic properties of all its components must be known. During unit load resonance it is expected that the deck-board of the pallet will be subjected to loading at rates much higher than those used in standard bending test. As the rate of loading increases the wood becomes effectively stiffer. To determine the effect that loading rate had on the elastic properties of wood, a series of bending tests were conducted on a variety of species commonly used to construct pallets. The results of these tests were then used to develop a mathematical model for estimating the stiffness over a range of loading rates. This model would then be used to estimate the elastic properties of the deck-board members for input into the RoPUL model.

A 2.0 Material

The deck-boards used in the bending test were manufactured from clear dry (averaging 9.5% mc) boards. The eight boards used represented three species including two yellow-poplar (*Liriodendron tulipifera*) boards, four red oak (*Quercus spp*) boards, and two hard maple (*Acer spp*) boards. Each board was dressed to 0.4 inch by 3.0 inch. The dressed boards were then sawn into three pieces, an 18-inch long test specimen, and a random length piece used to determine moisture content and specific gravity, and a second random length

control sample used to monitor moisture content changes during subsequent testing.

A 3.0 Methods

The moisture content of each board was measured following ASTM D-2016 method A oven-drying method. The testing specimens and control samples were stored together in the testing facility, which is maintained at approximately 70° F temperature and 50% relative humidity. The oven dry moisture content samples were then used to calculate the specific gravity of each board using ASTM D –2395 method B volume by water immersion.

Preliminary tests had determined that the maximum rate of deformation possible on the MTS universal tester used, was approximately 100-inches per minute. A typical loading rate for pallet deck-boards utilizing ASTM D-198 would be approximately 0.2-inches per minute (Kyokong 1979). For the purpose of this study 0.2-inches per minute will be considered the “standard” loading rate to which other rates will be compared. The modulus of elasticity of each test specimen was determined at six different rates of loading ranging from approximately an order of magnitude slower than the 0.2-inches per minute standard to the capacity of the testing equipment more than two orders of magnitude faster than the standard.

To determine the moduli of elasticity each specimen was nondestructively tested using a concentrated center-loading bending test with a 14-inch span. The test setup for the bending test is shown in Figure A1.

For each test the loading rate was determined from linear portion of the deflection-time curve (Figure A2).

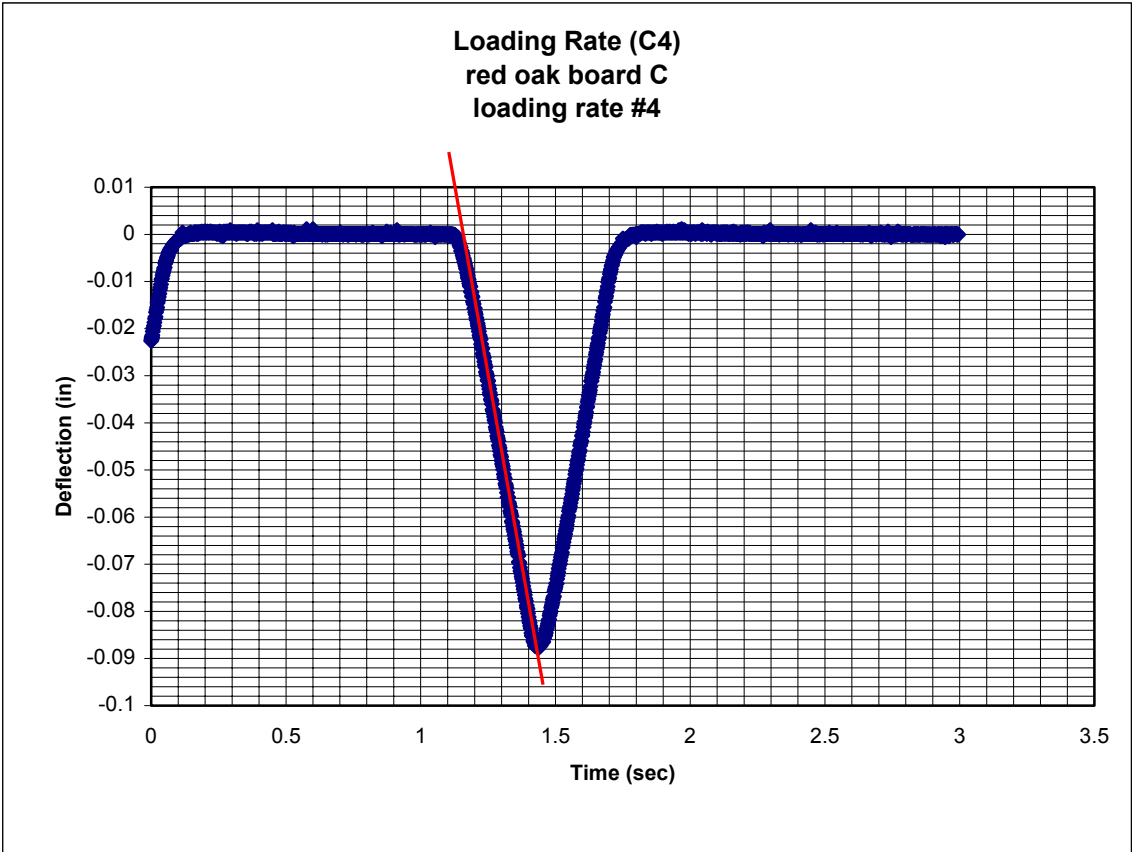


Figure A2. Typical deflection-time curve for deck-board stiffness test

During this period of the test the rate of deformation was constant. The load-deflection data collected during the test at constant rate of loading was then used to calculate the modulus of elasticity using Equation 8. A typical load-deflection curve is shown in Figure A3. Least squares regression analysis was then used to develop a model for estimating the modulus of elasticity of a board at high rates of loading. This model would then be used to estimate the effective stiffness of pallet deck-boards during unit load resonance.

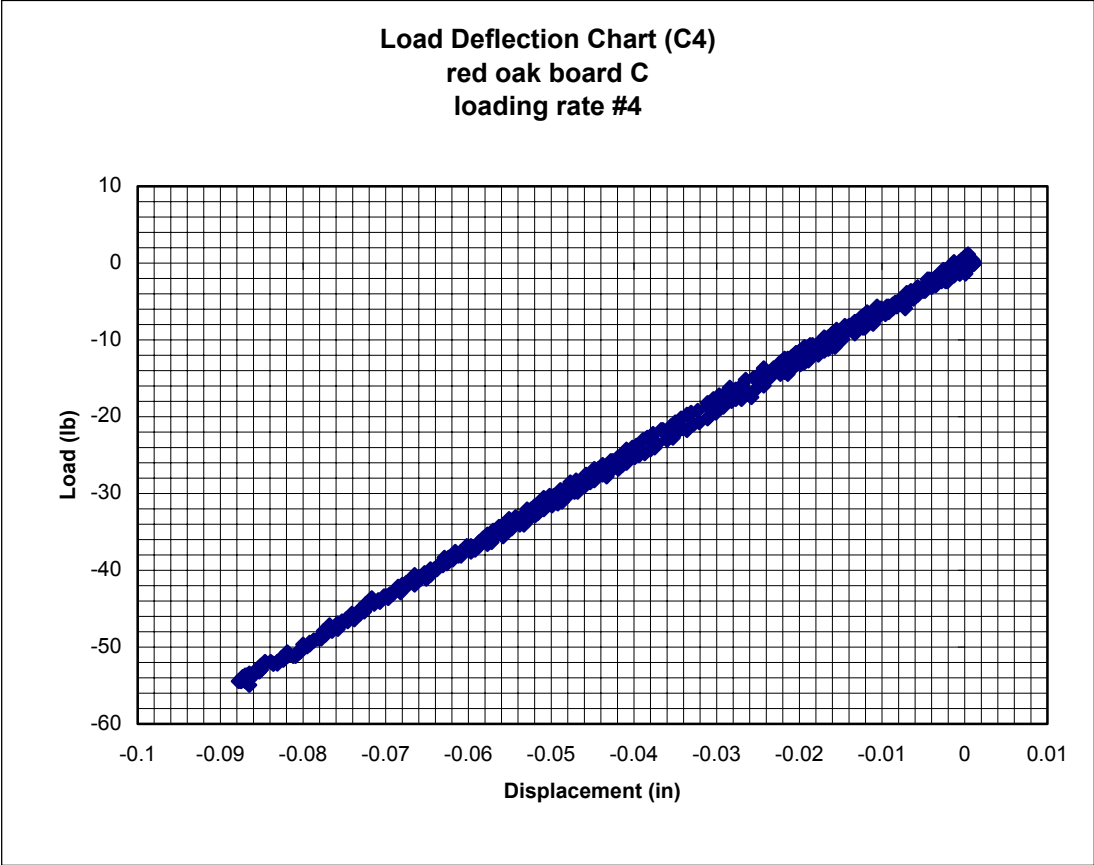


Figure A3. Typical load-deflection curve for deck-board stiffness test

4.0 Results

Measurements of the matched control samples, prior to each testing session, revealed no significant changes in the moisture content of the test samples during the testing period. The moisture content and specific gravity of each sample at the time of testing is shown in Table A1.

Table A1. Moisture content and specific gravity of samples at time of test.

Sample	Species	Moisture Content %	Specific Gravity
A	Yellow poplar	9.3	0.56
B	Yellow poplar	9.5	0.56
C	Red oak	9.6	0.63
D	Red oak	9.3	0.71
E	Red oak	9.2	0.63
F	Red oak	9.3	0.64
G	Hard maple	9.5	0.67
H	Hard maple	10.4	0.68

The average rate of deformation for each test series is shown in Table A2.

Table A2. Average rates of deformation for bending test.

Test #	1	2	3	4	5	6
Average Loading rate (in/min)	0.01	0.2	2.0	20.0	88.0	96.0

As can be seen in Figure A4 each test sample exhibited a similar pattern of increasing stiffness as the loading rate increased. Least squares regression analysis was used to develop a model describing this pattern. The independent variables chosen for this model were the Modulus of Elasticity as measured by a standard static test (ASTM D-1234), and the rate of loading used in the dynamic test. Initially the data was fitted to a linear model (Model 1) with the form:

$$dE = a + b(sE) + c(\text{rate})$$

dE = dynamic Modulus of elasticity (psi)

sE = static Modulus of elasticity (psi)

rate = rate of loading (in/min)

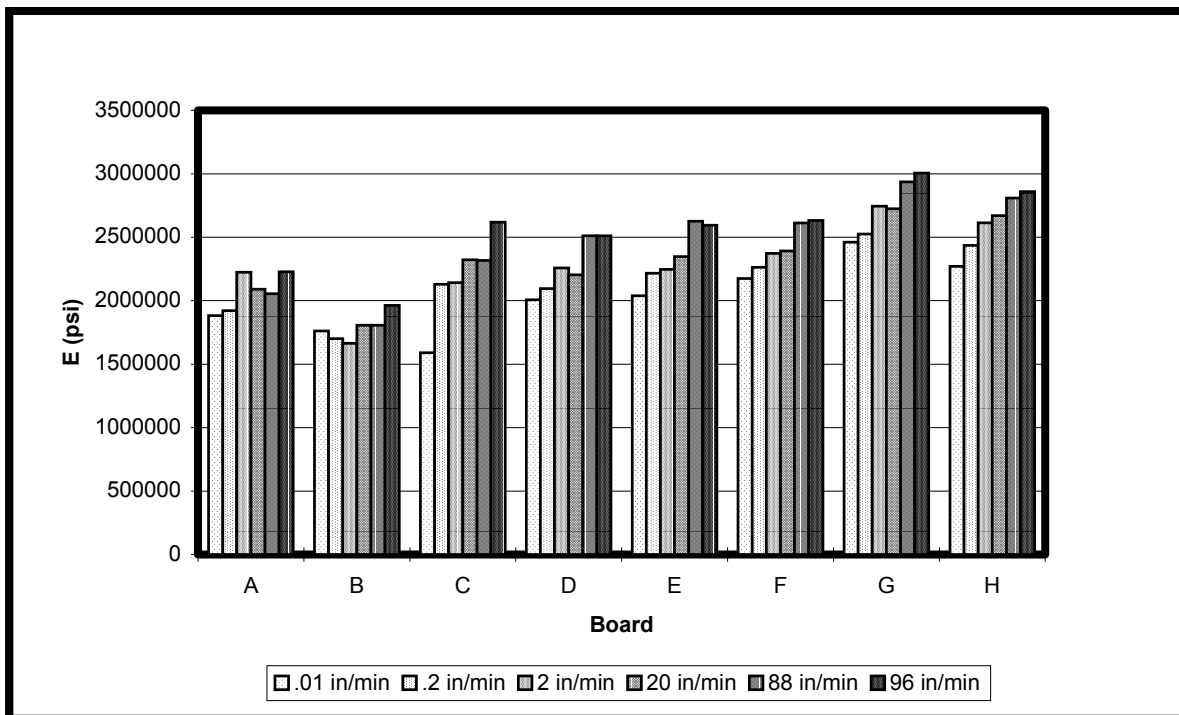


Figure A4. Affect of loading rate on the modulus of elasticity of pallet deck-boards

The results of this regression analysis are shown in Table A3.

Table A3. Regression output for Model 1
SUMMARY OUTPUT

$$dE = a + b(sE) + c(\text{rate})$$

<i>Regression Statistics</i>	
Multiple R	0.90884
R Square	0.82598
Adjusted R Square	0.81658
Standard Error	152580.9156
Observations	40

<i>ANOVA</i>					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	4.08864E+12	2.04432E+12	87.81100561	8.93264E-15
Residual	37	8.61395E+11	23280935808		
Total	39	4.95004E+12			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	-293273	204796	-1	0
sE	1.1650	0.0936	12.4470	0.0000
rate	2605	573	5	0

While all the variables (other than the intercept) appear significant a review of the residual plots (Figures A5-a and A5-b) indicates that Model 1 may not be the most appropriate. The plot of the residuals for the independent variable **sE** displays a random distribution of points. This would indicate that this variable was properly specified. The plot of the residuals for the independent variable **rate**, however, has a distinctive curved pattern. This indicates that a higher order model would be more appropriate.

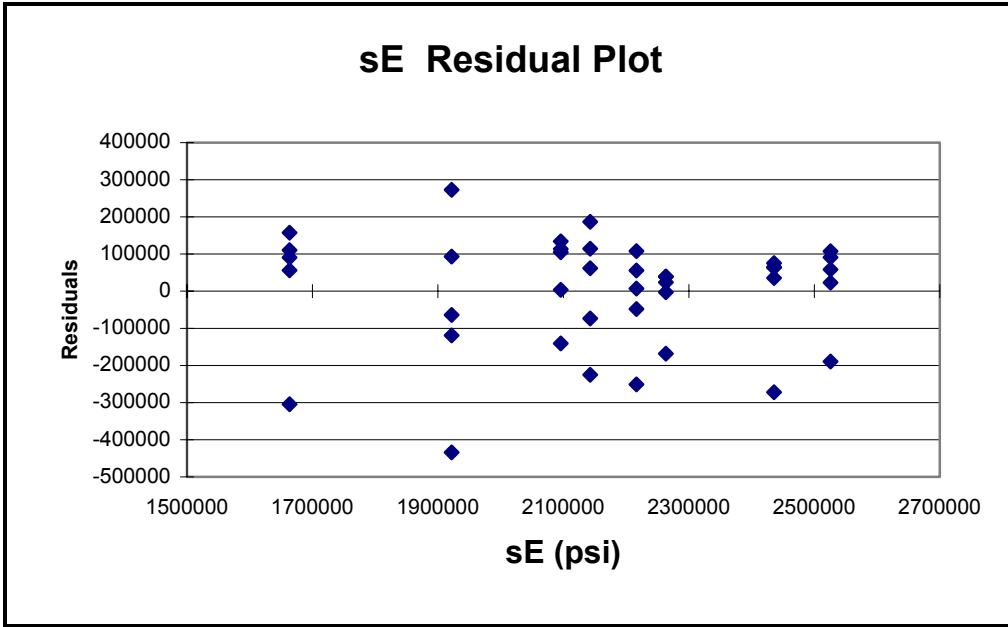


Figure A5-a. Residual plot for **sE** variable in Model 1

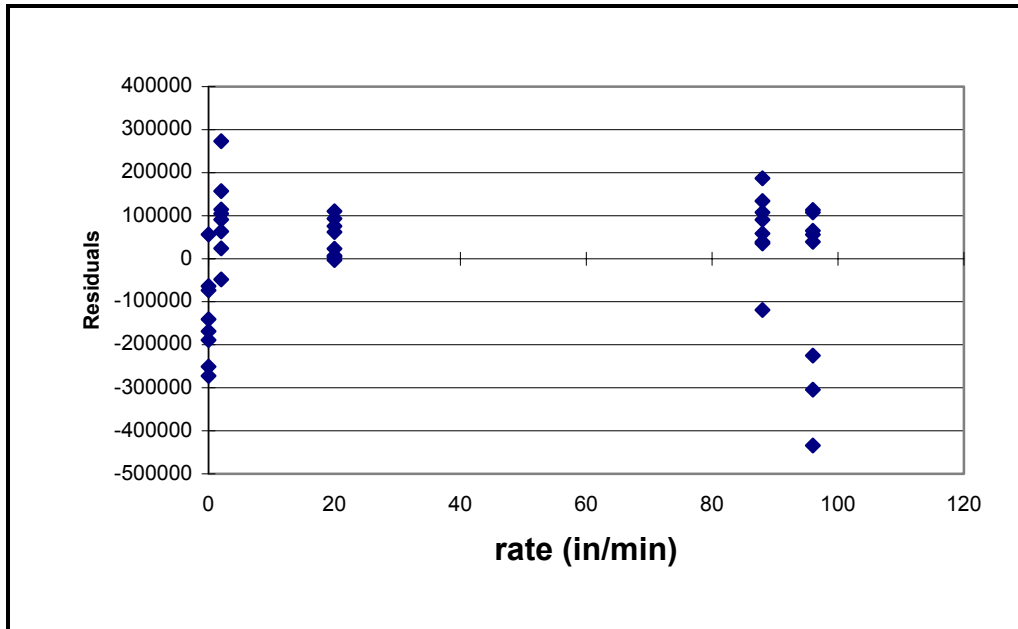


Figure A5-b. Residual plot for **rate** variable in Model 1

As a result, a second model (Model 2) was fitted to the data introducing a logarithmic term for the second independent variable $\ln(\text{rate})$. The form of Model 2 is:

$$DE = a + b(\text{sE}) + c(\ln(\text{rate}))$$

dE = dynamic Modulus of elasticity (psi)
sE = static Modulus of elasticity (psi)
rate = rate of loading (in/min)

The results of this regression analysis are shown in Table A4.

Table A4. Regression output for Model 2

SUMMARY OUTPUT

$$dE = a + b (\text{sE}) = c (\ln(\text{rate}))$$

<i>Regression Statistics</i>	
Multiple R	0.9330
R Square	0.8705
Adjusted R Square	0.8635
Standard Error	131616.7021
Observations	40

ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	4.31E+12	2.15E+12	124.3751	3.77E-17
Residual	37	6.41E+11	1.73E+10		
Total	39	4.95E+12			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	-248988	175760	-1.4166	0.1650
sE	1.1650	0.0807	14.4296	8.99E-17
$\ln(\text{rate})$	38789	6092	6.3668	2.00E-07

As with Model 1, all of the independent variable other than the intercept are significant in Model 2. A review of the residual output for Model 2 (Figures A6-a and A6-b) indicates that the model was correctly specified.

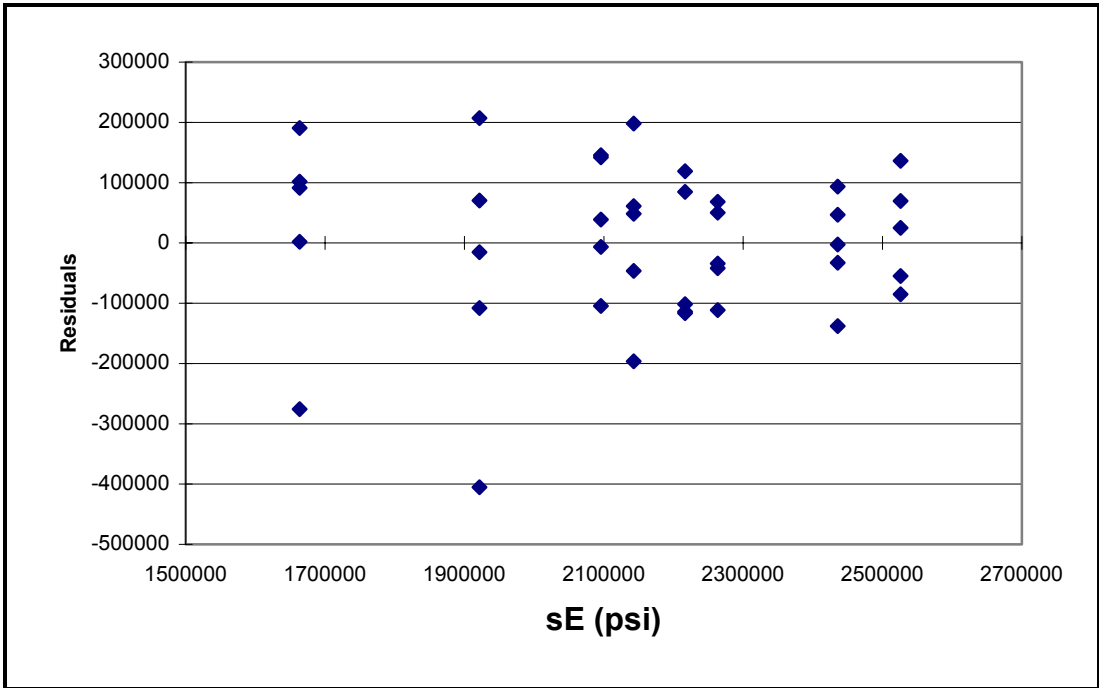


Figure A6-a. Residual plot for **sE** variable in Model 2

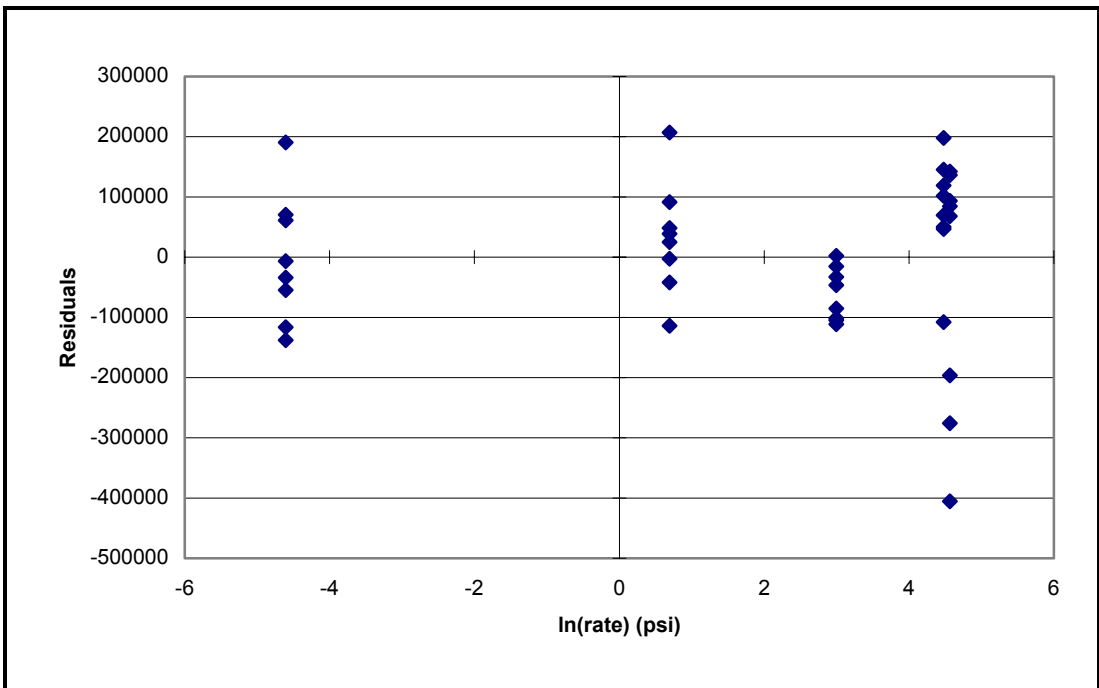


Figure A6-b. Residual plot for **ln(rate)** variable in Model 2

A 5.0 Discussion

The results of this study show that the stiffness of wood is directly related to the rate at which a load is applied. Analysis of the data indicates that of the models reviewed the most appropriate one is a logarithmic model in the form:

$$DE = -25000 + 1.165(\mathbf{sE}) + 38800(\ln(\mathbf{rate}))$$

dE = dynamic Modulus of elasticity (psi)

sE = static Modulus of elasticity (psi)

rate = rate of loading (in/min)

Appendix B Validation of the joint stiffness model

B 1.0 Nail head embedment and shank withdrawal stiffness

B 1.1 Introduction

To accurately predict the natural frequencies of a beam the type of support at the ends of the beam must be known. The end of a pallet deck-board (the deck-board stringer joint) can be best described as a semi-rigid connection.

Samarasinghe (1987) developed a series of equations that could be used to model the degree of rigidity of block pallet joints. This model idealized a pallet joint as a beam supported by linear elastic springs representing the contribution of the nail shank resistance to withdrawal, nail head embedment resistance, and edge compression stiffness to the overall joint rotational stiffness. Samarasinghe developed regression models for predicting each of these stiffnesses based on joint parameters. In this study both the nail shank withdrawal, and head embedment stiffness models were developed from empirical data, while the compression stiffness was developed from derived data developed from simulations of actual joint rotation test. These models were originally developed to predict the static deflection of wooden pallets. A series of test were performed to determine if these models could be used to describe the behavior of a stringer pallet joint for use in the RoPUL model. Nailed joints were subjected to axial withdrawal to measure the combined effect of the nails head embedment stiffness and the shank withdrawal stiffness. These values were then compared to values calculated using the models developed by Samarasinghe.

B 1.2 Materials

The deck-boards and stringers used to construct the joints were manufactured from clear dry boards. Eight deck-boards, two each of southern yellow pine (*Pinus spp*), hard maple *Acer spp*), Yellow-poplar (*Liriodendron tulipifera*), and red oak (*Quercus spp*), were dressed to 0.4 inches by 3.0 inches. Each board was then sawn into three pieces, a six inch long piece used to make the test joint, and two randomly sized pieces one used to determine the boards moisture content and specific gravity the other a control sample used to monitor moisture content changes in the wood during the testing period. Two stringers, one each of white oak (*Quercus spp*), and one of southern yellow pine (*Pinus spp*), were dressed to 1.25 inches by 4.0 inches. From these boards five oak stringers and 3 pine stringers for use in the joint test were sawn, along with a moisture content and specific gravity sample, and a control sample from each stringer.

B 1.3 Methods

The testing specimens and control samples were stored together in the testing facility, which was maintained at approximately 70° F temperature and 50% relative humidity. The moisture content of each board was measured following ASTM D-2016 method A oven dry method. The oven dry moisture content samples were then used to calculate the specific gravity of each board using ASTM D-2395 method B volume by water immersion. The moisture content and specific gravity of each board is shown in Table B1.

Table B1. Moisture content and specific gravity of test boards

Board*	Moisture content (%)	Specific gravity
SYP deck-board 1	7.76	0.54
SYP deck-board 2	7.69	0.52
HM deck-board 1	6.32	0.55
HM deck-board 2	6.44	0.68
YP deck-board 1	6.82	0.59
YP deck-board 2	6.75	0.59
RO deck-board 1	7.53	0.76
RO deck-board 2	7.91	0.80
WO stringer	10.57	0.67
SYP stringer	8.33	0.53

*SYP = southern yellow pine
 HM = hard maple
 YP = yellow-poplar
 RO = red oak
 WO = white oak

From these boards eight test joints were constructed the board combinations are shown in table B2.

Table B2. Board combinations of the test joints

Test joint	Deck-board	Stringer
Sypnt1a	SYP deck-board 1	WO stringer
Sypnt1b	SYP deck-board 2	WO stringer
Mnt1b	HM deck-board 1	WO stringer
Mnt2a	HM deck-board 2	SYP stringer
Ypnt1b	YP deck-board 1	WO stringer
Ypnt2a	YP deck-board 2	SYP stringer
Ont1b	RO deck-board 1	WO stringer
Ont2b	RO deck-board 2	SYP stringer

Test specimens were preload to 10 pounds. Deflection measurements were taken at 25-pound intervals through 175 pounds at which time the test was terminated. A typical load deflection plot is shown in Figure B1.

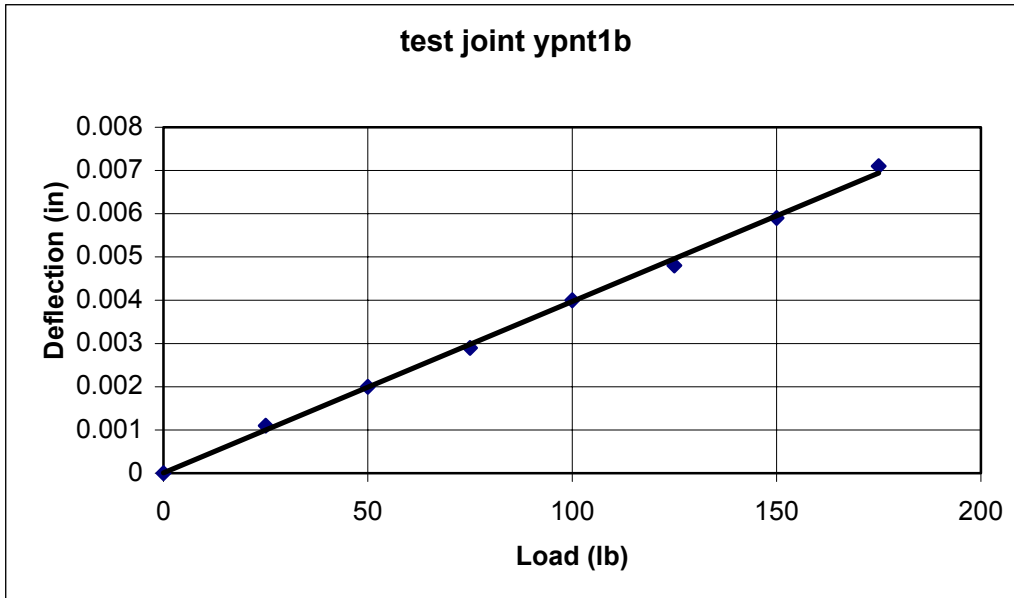


Figure B1. Typical joint separation load-deflection plot

The combined head embedment and shank withdrawal stiffness of each test joint was then calculated from the linear portion of each load-deflection plot. Values for the head embedment and shank withdrawal stiffness of each joint was also calculated based on the equations developed by Samarasinghe. For head embedment:

$$K_{hp} = - 10245 + 91628(SG_d) \quad (B1)$$

K_{hp} = head embedment stiffness
 SG_d = specific gravity of deck-board

And for the shank withdrawal stiffness:

$$K_{wds} = 18976 + 62899 (SG_s)^3 \quad (B2)$$

K_{wds} = shank withdrawal stiffness
 SG_s = specific gravity of the stringer

Since these two factors are working in series the combined separation stiffness of the joint can be calculated as:

$$K_n = \frac{1}{\left(\frac{1}{K_{hp}} + \frac{1}{K_{wds}} \right)} \quad (B3)$$

B 1.4 Results

The results of the joint separation test are listed in Table B3.

Table B3. Measured and estimated joint separation stiffness values

Test joint	Measured separation stiffness K lbs/in	Estimated separation stiffness K lbs /in
Sypnt1a	22800	23900
Sypnt1b	25522	23200
Mnt1b	22900	24200
Mnt2a	22900	26100
Ypnt1b	25200	25500
Ypnt2a	23100	23800
Ont1b	25700	30100
Ont2b	22500	28800

B 2.0 Edge compression stiffness

B 2.1 Introduction

The edge compression stiffness model developed by Samarasinghe was tested to determine if it also could be used in the RoPUL model. Because of the difficulties in directly measuring the joints edge compression stiffness and area being compressed the model will be tested indirectly by looking at the ability of a RoPUL model (using the estimated nail and edge compression stiffness values) to predict the center span deflection of a single span pallet section. The testing was a two-step process. First the RoPUL model was used to predict the center deflection of a simply supported deck-board. This was done to confirm the ability of the model to accurately describe the behavior of the deck-board, before introducing the joint components of the model. These deck-boards were then used to construct single span pallet sections for use in testing the edge compression stiffness. Once the model was determined to accurately predict the center deflection of a simply supported deck-board the RoPUL model was modified by adding springs representing a nailed joint to either end of the deck-board, and the deflections at center span were again compared to those measured during testing.

B 2.2 Materials

The deck-boards used in this series of test were manufactured from clear dry (averaging 6.5%) boards. The eight boards used two each of yellow-poplar

(*Liriodendron tulipifera*), red oak (*Quercus spp*), hard maple (*Acer spp*), southern yellow pine (*Pinus spp.*). Four of the board (one of each species will be used for the simply supported bending test. These same boards will be utilized to make the top deck for the pallet sections to be used in the edge compression bending tests. The other four boards will be used for the bottom deck of the pallet sections. Single span sections assemble using a single nail (same fastener used in the joint separation test (appendix B1). Each board was dressed to 0.4 inch by 3.0 inch. The dressed boards were then sawn into three pieces, an 18-inch long test specimen, and a random length piece used to determine moisture content and specific gravity, and a second random length control sample used to monitor moisture content changes during subsequent testing. No significant moisture content changes occurred during subsequent testing.

B 2.3 Methods

The moisture content of each board was measured following ASTM D-2016 method A oven-drying method. The testing specimens and control samples were stored together in the testing facility, which is maintained at approximately 70° F temperature and 50% relative humidity. The oven dry moisture content samples were then used to calculate the specific gravity of each board using ASTM D –2395 method B volume by water immersion.

The simply supported bending test were done in the same manner as the modulus of elasticity test described in Appendix A, with the standard loading rate of 0.2 inches per minute being used (Kyokong 1979). Data from the tests was

used to calculate the modulus of elasticity for each board as described in appendix A. This information will be used later as an input variable for the RoPUL model. A sample RoPUL input file and output for the simply supported test can be found in Appendix B. The center span deflections measured at 75 lbs. of load were compared to a RoPUL model of each deck-board.

The edge compression test used the same procedure described above with the exception that the nailed joint was now providing the end support for the deck-board. The free span of the pallet section was the same used for the simply supported test 14 inches. The center span deflections measured at 75 lbs. of load were compared to a RoPUL model of each pallet section. A sample RoPUL input file for the edge compression test can be found in Appendix B.

B 2.4 Results

The results of the simply supported bending test are shown in Figure B2. The results ranged from an under estimate of the deflection of 3.8% for the hard maple board and an over estimate of 6.3% for the southern yellow pine board. The RoPUL model on average over predicted the center deflection by 1.1%.

The results of the edge compression bending tests are shown in Figure B3. The results ranged from an over estimation of the deflection by the RoPUL model of 12.3% for the hard maple board to an over estimation of 27.1% for the southern yellow pine board. The RoPUL model on

average over predicted the center deflection by 18.5%. This would indicate that the edge compression stiffness values used in the RoPUL models are too low and a different model might be more appropriate.

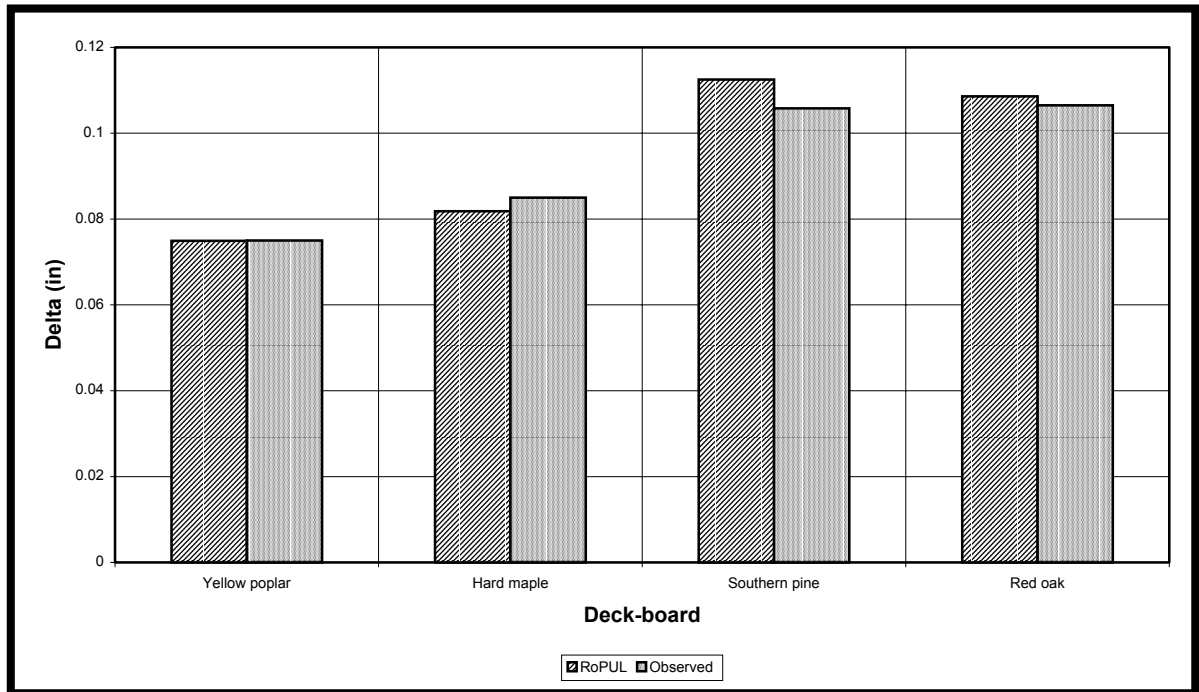


Figure B 2. Comparison of center deflection of a simply supported deck-board predicted by RoPUL to measured deflection of the deck-board with a 75# concentrated load.

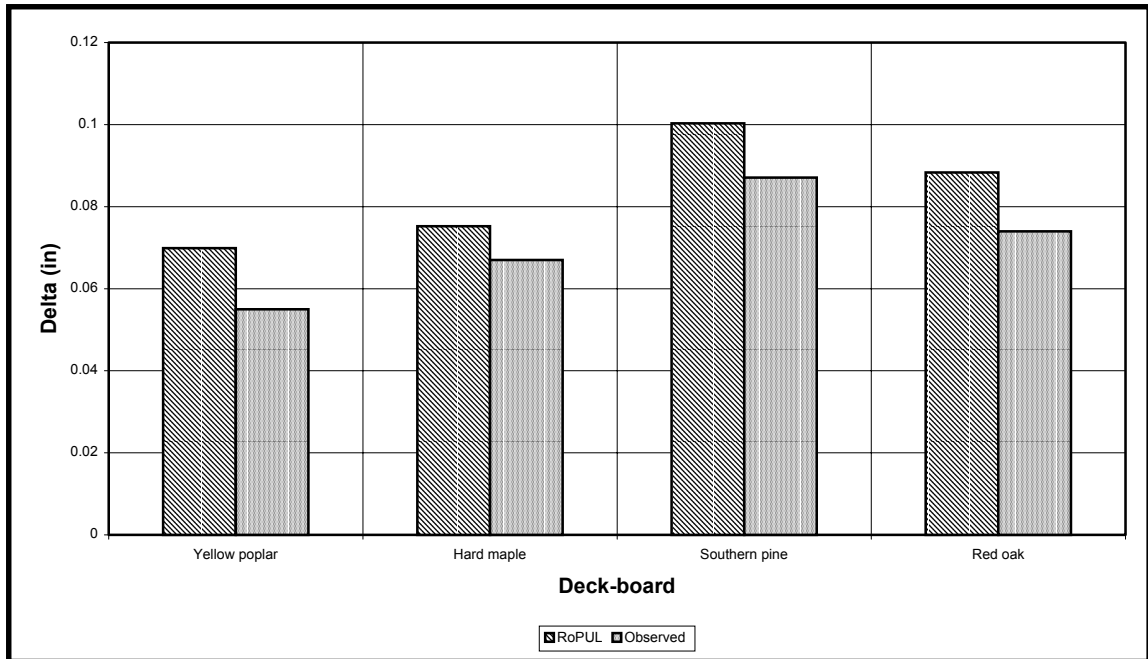


Figure B 3. Comparison of center deflection of the top deck of a pallet section predicted by RoPUL to measured deflection of the top deck with a 75# concentrated load.

B 2.5 Sample input and output file for the RoPUL model of a simply supported deck-board

C This is file OAK1A written by SAPIN on Tue Jan 31 15:53:14 1995

C Units are KIP INCHES

C model of deck board oak1

C simply supported static bending test

C 14" span center loading

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID (sets up a two-dimensional grid for laying out the model note the y plane has no thickness)

XN=21 YN=1 ZN=11
0 1 2 3 4 5 6 7
8 9 10 11 12 13 14 15
16 17 18 19 20
0
0 1 2 3 4 5 6 7
8 9 10

JOINTS (sets the locations of the joint nodes within the grid)

1 X=2 Y=0 Z=2
2 X=2.5 Y=0 Z=2
3 X=3 Y=0 Z=2
4 X=4 Y=0 Z=2
5 X=5 Y=0 Z=2
6 X=6 Y=0 Z=2
7 X=7 Y=0 Z=2
8 X=8 Y=0 Z=2
9 X=9 Y=0 Z=2
10 X=10 Y=0 Z=2
11 X=11 Y=0 Z=2
12 X=12 Y=0 Z=2
13 X=13 Y=0 Z=2
14 X=14 Y=0 Z=2
15 X=15 Y=0 Z=2
16 X=16 Y=0 Z=2
17 X=17 Y=0 Z=2
18 X=17.5 Y=0 Z=2
19 X=18 Y=0 Z=2

FRAME (defines the mechanical and physical properties of the frame elements used and defines their location by the nodes located at their endpoints)

NM=1 NL=0 NSEC=0

1 SH=R T=3.015,0.402 E=2455.1 G=153.4 W=3.4368E-05 M=8.8945E-08 TC=0

1 1 2 M=1,1,1 LP=1,0 MS= 0,0

2 2 3 M=1,1,1 LP=1,0 MS= 0,0

3 3 4 M=1,1,1 LP=1,0 MS= 0,0

4 4 5 M=1,1,1 LP=1,0 MS= 0,0

5 5 6 M=1,1,1 LP=1,0 MS= 0,0
 6 6 7 M=1,1,1 LP=1,0 MS= 0,0
 7 7 8 M=1,1,1 LP=1,0 MS= 0,0
 8 8 9 M=1,1,1 LP=1,0 MS= 0,0
 9 9 10 M=1,1,1 LP=1,0 MS= 0,0
 10 10 11 M=1,1,1 LP=1,0 MS= 0,0
 11 11 12 M=1,1,1 LP=1,0 MS= 0,0
 12 12 13 M=1,1,1 LP=1,0 MS= 0,0
 13 13 14 M=1,1,1 LP=1,0 MS= 0,0
 14 14 15 M=1,1,1 LP=1,0 MS= 0,0
 15 15 16 M=1,1,1 LP=1,0 MS= 0,0
 16 16 17 M=1,1,1 LP=1,0 MS= 0,0
 17 17 18 M=1,1,1 LP=1,0 MS= 0,0
 18 18 19 M=1,1,1 LP=1,0 MS= 0,0

RESTRAINTS (defines any restraints at each node location)

1 1 1 R=0,1,0,1,0,1
 4 4 1 R=0,1,0,1,0,1
 5 5 1 R=0,1,0,1,0,1
 6 6 1 R=0,1,0,1,0,1
 7 7 1 R=0,1,0,1,0,1
 8 8 1 R=0,1,0,1,0,1
 9 9 1 R=0,1,0,1,0,1
 10 10 1 R=0,1,0,1,0,1
 11 11 1 R=0,1,0,1,0,1
 12 12 1 R=0,1,0,1,0,1
 13 13 1 R=0,1,0,1,0,1
 14 14 1 R=0,1,0,1,0,1
 15 15 1 R=0,1,0,1,0,1
 16 16 1 R=0,1,0,1,0,1
 19 19 1 R=0,1,0,1,0,1
 2 2 1 R=0,1,0,1,0,1
 18 18 1 R=0,1,0,1,0,1
 3 3 1 R=0,1,1,1,0,1
 17 17 1 R=0,1,1,1,0,1

SPRINGS (defines the location (node) and stiffness of each spring restraint)

3 3 1 K=0.0005,0,0,0,0,0
17 17 1 K=0.0005,0,0,0,0,0

LOADS (defines the location (node) and magnitude of each load)

10 10 1 L=1 F=0,0,-0.075,0,0,0

Output file

CSI / SAP90 - - FINITE ELEMENT ANALYSIS OF STRUCTURES PAGE 6

PROGRAM:SAP90/FILE:oak1a.SOL

JOINT DISPLACEMENTS

LOAD CONDITION 1 - DISPLACEMENTS "U" AND ROTATIONS "R"

JOINT	U(X)	U(Z)	R(Y)
1	.000000	.022927	.022927
2	.000000	.011463	.022927
3	.000000	.000000	.022927
4	.000000	-.023013	.022459
5	.000000	-.045090	.021055
6	.000000	-.065296	.018716
7	.000000	-.082694	.015441
8	.000000	-.096349	.011229
9	.000000	-.105325	.006083
10	.000000	-.108686	.000000 (center span)
11	.000000	-.105325	-.006083
12	.000000	-.096349	-.011229
13	.000000	-.082694	-.015441
14	.000000	-.065296	-.018716
15	.000000	-.045090	-.021055
16	.000000	-.023013	-.022459
17	.000000	.000000	-.022927
18	.000000	.011463	-.022927
19	.000000	.022927	-.022927

REACTIONS AND APPLIED FORCES

LOAD CONDITION 1 - FORCES "F" AND MOMENTS "M"

JOINT	F(Z)	M(Y)	
1	.0000	.0000	
2	.0000	.0000	
3	.0375	.0000	support
4	.0000	.0000	
5	.0000	.0000	
6	.0000	.0000	
7	.0000	.0000	
8	.0000	.0000	
9	.0000	.0000	
10	-.0750	.0000	center span
11	.0000	.0000	
12	.0000	.0000	
13	.0000	.0000	
14	.0000	.0000	
15	.0000	.0000	
16	.0000	.0000	
17	.0375	.0000	support
18	.0000	.0000	
19	.0000	.0000	

TOTAL .4770E-17 .7746E-14

B 2.6 Typical RoPUL input and output file for the edge compression pallet section

(file is identical to oak1a above with the exception of the spring section)

C This is file OAK1NS written by SAPIN on Sun Apr 06 23:03:41 1997

C pallet section with oak1a top deck 14" span for edge compression stiffness test

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=21 YN=1 ZN=11

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20

0

0 1 2 3 4 5 6 7

8 9 10

JOINTS

1 X=2 Y=0 Z=2

2 X=2.5 Y=0 Z=2

3 X=3 Y=0 Z=2

4 X=4 Y=0 Z=2

5 X=5 Y=0 Z=2

6 X=6 Y=0 Z=2

7 X=7 Y=0 Z=2

8 X=8 Y=0 Z=2

9 X=9 Y=0 Z=2

10 X=10 Y=0 Z=2

11 X=11 Y=0 Z=2

12 X=12 Y=0 Z=2

13 X=13 Y=0 Z=2

14 X=14 Y=0 Z=2

15 X=15 Y=0 Z=2

16 X=16 Y=0 Z=2

17 X=17 Y=0 Z=2

18 X=17.5 Y=0 Z=2

19 X=18 Y=0 Z=2

FRAME

NM=1 NL=0 NSEC=0

1 SH=R T=3.015,0.402 E=2455.1 G=153.4 W=3.4368E-05 M=8.8945E-08 TC=0

1 1 2 M=1,1,1 LP=1,0 MS= 0,0
3 3 4 M=1,1,1 LP=1,0 MS= 0,0
4 4 5 M=1,1,1 LP=1,0 MS= 0,0
5 5 6 M=1,1,1 LP=1,0 MS= 0,0
6 6 7 M=1,1,1 LP=1,0 MS= 0,0
7 7 8 M=1,1,1 LP=1,0 MS= 0,0
8 8 9 M=1,1,1 LP=1,0 MS= 0,0
9 9 10 M=1,1,1 LP=1,0 MS= 0,0
10 10 11 M=1,1,1 LP=1,0 MS= 0,0
11 11 12 M=1,1,1 LP=1,0 MS= 0,0
12 12 13 M=1,1,1 LP=1,0 MS= 0,0
13 13 14 M=1,1,1 LP=1,0 MS= 0,0
14 14 15 M=1,1,1 LP=1,0 MS= 0,0
15 15 16 M=1,1,1 LP=1,0 MS= 0,0
16 16 17 M=1,1,1 LP=1,0 MS= 0,0
18 18 19 M=1,1,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=0,1,0,1,0,1
4 4 1 R=0,1,0,1,0,1
5 5 1 R=0,1,0,1,0,1
6 6 1 R=0,1,0,1,0,1
7 7 1 R=0,1,0,1,0,1
8 8 1 R=0,1,0,1,0,1
9 9 1 R=0,1,0,1,0,1
10 10 1 R=0,1,0,1,0,1
11 11 1 R=0,1,0,1,0,1
12 12 1 R=0,1,0,1,0,1
13 13 1 R=0,1,0,1,0,1
14 14 1 R=0,1,0,1,0,1
15 15 1 R=0,1,0,1,0,1
16 16 1 R=0,1,0,1,0,1
19 19 1 R=0,1,0,1,0,1

2 2 1 R=0,1,0,1,0,1
18 18 1 R=0,1,0,1,0,1
3 3 1 R=0,1,0,1,0,1
17 17 1 R=0,1,0,1,0,1

SPRINGS

2 2 1 K=0.0005,0,31.7,0,0,0 **(31.7 is the nail stiffness)**
18 18 1 K=0.0005,0,31.7,0,0,0
3 3 1 K=0,0,24.5,0,0,0 **(24.4 is the edge compression stiffness)**
17 17 1 K=0,0,24.5,0,0,0

LOADS

10 10 1 L=1 F=0,0,-0.075,0,0,0

Appendix C Validation of the product model (stacked apples)

C 1.0 Introduction

Much of the validation testing in this study involves the use of a steel plate to simulate the product. The steel plate was chosen because it closely resemble an idealized product who's natural frequency would be high enough not to influence the natural frequency of the other model components (i.e. it would behave as an idealized mass). This is particularly true when trying to determine the effective stiffness of the corrugated sheets under various load levels. To validate the product model a very different product was chosen. An apple when compared to the steel plate used in previous test is much less stiff and less dense than the steel plate. As such it should have a much lower natural frequency.

C 2.0 Materials

Ten freshly picked red delicious apples were chosen at random from those to be used in the full-scale model validation test. The average weight and size of the apples had been determined previously (section 5.1), along with their natural frequency for use in calculating an effective column stiffness for use in the RoPUL model. The corrugated board used for this series of test was 250# burst test C-flute board that had been used previously in validating the pallet model (section 5.4). The pallet section used was constructed of the same

material and manner as the yellow-poplar pallet used in the full-scale verification test.

C 3.0 Methods

Each test consisted of single log sweep from 5 hertz to 100 hertz of a loaded pallet section. Acceleration measurements were made during each test by piezo-electric accelerometers attached to the top apple in the stack. Three sets of test were done. One set with only a single apple placed on a sheet of corrugated board center span on the pallet section, a second series with a column of two apples similarly place, and a third with a column of three apples at center span. The resonant frequency of each loaded pallet section was determined from the peak output acceleration recorded during the test. For each of the three tests a RoPUL model was constructed. The resonant frequency predicted by the RoPUL model was then compared to the observed resonant frequency.

C 3.1 RoPUL input and output file for model with a single apple

2 span model with 275# c-flute, column of apples

C This is file 1apple written by SAPIN on Thu Sep 03 22:18:21 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=61 YN=1 ZN=21

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51 52 53 54 55

56 57 58 59 60

0

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20

JOINTS

1 X=10 Y=0 Z=5

2 X=10.35 Y=0 Z=5

3 X=10.6 Y=0 Z=5

4 X=11 Y=0 Z=5

5 X=20.375 Y=0 Z=5

6 X=29.5 Y=0 Z=5

7 X=29.9 Y=0 Z=5

8 X=30.1 Y=0 Z=5

9 X=30.5 Y=0 Z=5

10 X=39.625 Y=0 Z=5

11 X=49 Y=0 Z=5

12 X=49.4 Y=0 Z=5

13 X=49.6 Y=0 Z=5
14 X=50 Y=0 Z=5
100 X=20.375 Y=0 Z=5.17
101 X=39.625 Y=0 Z=5.17
200 X=18.875 Y=0 Z=8.17
201 X=20.375 Y=0 Z=8.17
202 X=21.875 Y=0 Z=8.17
203 X=38.125 Y=0 Z=8.17
204 X=39.625 Y=0 Z=8.17
205 X=41.125 Y=0 Z=8.17

FRAME

NM=4 NL=0 NSEC=0

1 SH=R T=0.1,3 E=29000 G=11154 W=0.00026352 M=6.8391E-07 TC=0
2 SH=R T=5.487,0.477 E=1711 G=106.9 W=8.1764E-05 M=2.1114E-07 TC=0
3 SH=R T=16,5 E=0.119 G=0.00417 W=0.00018584 M=4.8128E-06 TC=0
4 SH=R T=3,3 E=.121 G=0.00417 W=3.4776E-08 M=9E-11 TC=0
1 1 2 M=2,2,1 LP=1,0 MS= 0,0
2 2 3 M=2,2,1 LP=1,0 MS= 0,0
3 3 4 M=2,2,1 LP=1,0 MS= 0,0
4 4 5 M=2,2,1 LP=1,0 MS= 0,0
5 5 6 M=2,2,1 LP=1,0 MS= 0,0
6 6 7 M=2,2,1 LP=1,0 MS= 0,0
7 7 8 M=2,2,1 LP=1,0 MS= 0,0
8 8 9 M=2,2,1 LP=1,0 MS= 0,0
9 9 10 M=2,2,1 LP=1,0 MS= 0,0
10 10 11 M=2,2,1 LP=1,0 MS= 0,0
11 11 12 M=2,2,1 LP=1,0 MS= 0,0
12 12 13 M=2,2,1 LP=1,0 MS= 0,0
13 13 14 M=2,2,1 LP=1,0 MS= 0,0
14 5 100 M=3,3,1 LP=1,0 MS= 0,0
15 10 101 M=3,3,1 LP=1,0 MS= 0,0
116 100 201 M=4,4,1 LP=1,0 MS= 0,0
117 101 204 M=4,4,1 LP=1,0 MS= 0,0
118 200 201 M=1,1,1 LP=1,0 MS= 0,0
119 201 202 M=1,1,1 LP=1,0 MS= 0,0
120 203 204 M=1,1,1 LP=1,0 MS= 0,0

121 204 205 M=1,1,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=0,1,0,1,0,1
2 2 1 R=0,1,0,1,0,1
3 3 1 R=0,1,0,1,0,1
4 4 1 R=0,1,0,1,0,1
5 5 1 R=0,1,0,1,0,1
6 6 1 R=0,1,0,1,0,1
7 7 1 R=0,1,0,1,0,1
8 8 1 R=0,1,0,1,0,1
9 9 1 R=0,1,0,1,0,1
10 10 1 R=0,1,0,1,0,1
11 11 1 R=0,1,0,1,0,1
12 12 1 R=0,1,0,1,0,1
13 13 1 R=0,1,0,1,0,1
14 14 1 R=0,1,0,1,0,1
100 100 1 R=0,1,0,1,0,1
101 101 1 R=0,1,0,1,0,1
200 200 1 R=0,1,0,1,0,1
201 201 1 R=0,1,0,1,0,1
202 202 1 R=0,1,0,1,0,1
203 203 1 R=0,1,0,1,0,1
204 204 1 R=0,1,0,1,0,1
205 205 1 R=0,1,0,1,0,1

SPRINGS

1 1 1 K=0.1,0,24.1,0,0,0
14 14 1 K=0.1,0,24.1,0,0,0
4 4 1 K=0,0,38.7,0,0,0
6 6 1 K=0,0,38.7,0,0,0
9 9 1 K=0,0,38.7,0,0,0
11 11 1 K=0,0,38.7,0,0,0
2 2 1 K=0,0,35,0,0,0
3 3 1 K=0,0,35,0,0,0
7 7 1 K=0,0,35,0,0,0
8 8 1 K=0,0,35,0,0,0

12 12 1 K=0,0,35,0,0,0
13 13 1 K=0,0,35,0,0,0

Output file

C S I / S A P 9 0 - - FINITE ELEMENT ANALYSIS OF STRUCTURES
PAGE 2

PROGRAM:SAP90/FILE:1apple.RIT
2 span model with 275# c-flute, column of apples

E I G E N V A L U E S A N D F R E Q U E N C I E S

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.404019E+04	.635625E+02	10.116283	.098851
2	.451011E+04	.671573E+02	10.688422	.093559
3	.221128E+05	.148704E+03	23.666924	.042253
4	.127878E+06	.357600E+03	56.913824	.017570
5	.134618E+06	.366903E+03	58.394372	.017125

C 3.2 RoPUL input and output file for model with two apples

2 span model with 275# c-flute, column of apples

C This is file 2APPLE written by SAPIN on Sun Sep 13 22:39:11 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=61 YN=1 ZN=21

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51 52 53 54 55

56 57 58 59 60

0

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20

JOINTS

1 X=10 Y=0 Z=5

2 X=10.35 Y=0 Z=5

3 X=10.6 Y=0 Z=5

4 X=11 Y=0 Z=5

5 X=20.375 Y=0 Z=5

6 X=29.5 Y=0 Z=5

7 X=29.9 Y=0 Z=5

8 X=30.1 Y=0 Z=5

9 X=30.5 Y=0 Z=5

10 X=39.625 Y=0 Z=5

11 X=49 Y=0 Z=5

12 X=49.4 Y=0 Z=5

13 X=49.6 Y=0 Z=5

14 X=50 Y=0 Z=5
 100 X=20.375 Y=0 Z=5.17
 101 X=39.625 Y=0 Z=5.17
 200 X=18.875 Y=0 Z=8.17
 201 X=20.375 Y=0 Z=8.17
 202 X=21.875 Y=0 Z=8.17
 203 X=38.125 Y=0 Z=8.17
 204 X=39.625 Y=0 Z=8.17
 205 X=41.125 Y=0 Z=8.17
 300 X=18.875 Y=0 Z=11.17
 301 X=20.375 Y=0 Z=11.17
 302 X=21.875 Y=0 Z=11.17
 303 X=38.125 Y=0 Z=11.17
 304 X=39.625 Y=0 Z=11.17
 305 X=41.125 Y=0 Z=11.17

FRAME

NM=4 NL=0 NSEC=0

1 SH=R T=0.1,3 E=29000 G=11154 W=0.00026352 M=6.8391E-07 TC=0
 2 SH=R T=5.487,0.477 E=1711 G=106.9 W=8.1764E-05 M=2.1114E-07 TC=0
 3 SH=R T=16,5 E=0.119 G=0.00417 W=0.00018584 M=4.8128E-06 TC=0
 4 SH=R T=3,3 E=.121 G=0.00417 W=3.4776E-08 M=9E-11 TC=0
 1 1 2 M=2,2,1 LP=1,0 MS= 0,0
 2 2 3 M=2,2,1 LP=1,0 MS= 0,0
 3 3 4 M=2,2,1 LP=1,0 MS= 0,0
 4 4 5 M=2,2,1 LP=1,0 MS= 0,0
 5 5 6 M=2,2,1 LP=1,0 MS= 0,0
 6 6 7 M=2,2,1 LP=1,0 MS= 0,0
 7 7 8 M=2,2,1 LP=1,0 MS= 0,0
 8 8 9 M=2,2,1 LP=1,0 MS= 0,0
 9 9 10 M=2,2,1 LP=1,0 MS= 0,0
 10 10 11 M=2,2,1 LP=1,0 MS= 0,0
 11 11 12 M=2,2,1 LP=1,0 MS= 0,0
 12 12 13 M=2,2,1 LP=1,0 MS= 0,0
 13 13 14 M=2,2,1 LP=1,0 MS= 0,0
 14 5 100 M=3,3,1 LP=1,0 MS= 0,0
 15 10 101 M=3,3,1 LP=1,0 MS= 0,0

116 100 201 M=4,4,1 LP=1,0 MS= 0,0
117 101 204 M=4,4,1 LP=1,0 MS= 0,0
118 200 201 M=1,1,1 LP=1,0 MS= 0,0
119 201 202 M=1,1,1 LP=1,0 MS= 0,0
120 203 204 M=1,1,1 LP=1,0 MS= 0,0
121 204 205 M=1,1,1 LP=1,0 MS= 0,0
216 201 301 M=4,4,1 LP=1,0 MS= 0,0
217 204 304 M=4,4,1 LP=1,0 MS= 0,0
218 300 301 M=1,1,1 LP=1,0 MS= 0,0
219 301 302 M=1,1,1 LP=1,0 MS= 0,0
220 303 304 M=1,1,1 LP=1,0 MS= 0,0
221 304 305 M=1,1,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=0,1,0,1,0,1
2 2 1 R=0,1,0,1,0,1
3 3 1 R=0,1,0,1,0,1
4 4 1 R=0,1,0,1,0,1
5 5 1 R=0,1,0,1,0,1
6 6 1 R=0,1,0,1,0,1
7 7 1 R=0,1,0,1,0,1
8 8 1 R=0,1,0,1,0,1
9 9 1 R=0,1,0,1,0,1
10 10 1 R=0,1,0,1,0,1
11 11 1 R=0,1,0,1,0,1
12 12 1 R=0,1,0,1,0,1
13 13 1 R=0,1,0,1,0,1
14 14 1 R=0,1,0,1,0,1
100 100 1 R=0,1,0,1,0,1
101 101 1 R=0,1,0,1,0,1
200 200 1 R=0,1,0,1,0,1
201 201 1 R=0,1,0,1,0,1
202 202 1 R=0,1,0,1,0,1
203 203 1 R=0,1,0,1,0,1
204 204 1 R=0,1,0,1,0,1
205 205 1 R=0,1,0,1,0,1
300 300 1 R=0,1,0,1,0,1

301 301 1 R=0,1,0,1,0,1
 302 302 1 R=0,1,0,1,0,1
 303 303 1 R=0,1,0,1,0,1
 304 304 1 R=0,1,0,1,0,1
 305 305 1 R=0,1,0,1,0,1

SPRINGS

1 1 1 K=0.1,0,24.1,0,0,0
 14 14 1 K=0.1,0,24.1,0,0,0
 4 4 1 K=0,0,38.7,0,0,0
 6 6 1 K=0,0,38.7,0,0,0
 9 9 1 K=0,0,38.7,0,0,0
 11 11 1 K=0,0,38.7,0,0,0
 2 2 1 K=0,0,35,0,0,0
 3 3 1 K=0,0,35,0,0,0
 7 7 1 K=0,0,35,0,0,0
 8 8 1 K=0,0,35,0,0,0
 12 12 1 K=0,0,35,0,0,0
 13 13 1 K=0,0,35,0,0,0

Output file

C S I / S A P 9 0 - - FINITE ELEMENT ANALYSIS OF STRUCTURES
 PAGE 2

PROGRAM:SAP90/FILE:2apple.RIT
 2 span model with 275# c-flute, column of apples

E I G E N V A L U E S A N D F R E Q U E N C I E S

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.132300E+04	.363731E+02	5.788954	.172743
2	.139706E+04	.373773E+02	5.948785	.168102
3	.102550E+05	.101267E+03	16.117148	.062046
4	.226381E+05	.150460E+03	23.946397	.041760
5	.565082E+05	.237715E+03	37.833459	.026432

C 3.3 RoPUL input and output file for the model with three apples

2 span model with 275# c-flute, column of apples

C This is file YPapp2 written by SAPIN on Thu Sep 03 22:18:21 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=61 YN=1 ZN=21

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51 52 53 54 55

56 57 58 59 60

0

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20

JOINTS

1 X=10 Y=0 Z=5

2 X=10.35 Y=0 Z=5

3 X=10.6 Y=0 Z=5

4 X=11 Y=0 Z=5

5 X=20.375 Y=0 Z=5

6 X=29.5 Y=0 Z=5

7 X=29.9 Y=0 Z=5

8 X=30.1 Y=0 Z=5

9 X=30.5 Y=0 Z=5

10 X=39.625 Y=0 Z=5

11 X=49 Y=0 Z=5

12 X=49.4 Y=0 Z=5

13 X=49.6 Y=0 Z=5

14 X=50 Y=0 Z=5
 100 X=20.375 Y=0 Z=5.17
 101 X=39.625 Y=0 Z=5.17
 200 X=18.875 Y=0 Z=8.17
 201 X=20.375 Y=0 Z=8.17
 202 X=21.875 Y=0 Z=8.17
 203 X=38.125 Y=0 Z=8.17
 204 X=39.625 Y=0 Z=8.17
 205 X=41.125 Y=0 Z=8.17
 300 X=18.875 Y=0 Z=11.17
 301 X=20.375 Y=0 Z=11.17
 302 X=21.875 Y=0 Z=11.17
 303 X=38.125 Y=0 Z=11.17
 304 X=39.625 Y=0 Z=11.17
 305 X=41.125 Y=0 Z=11.17
 400 X=18.875 Y=0 Z=14.17
 401 X=20.375 Y=0 Z=14.17
 402 X=21.875 Y=0 Z=14.17
 403 X=38.125 Y=0 Z=14.17
 404 X=39.625 Y=0 Z=14.17
 405 X=41.125 Y=0 Z=14.17

FRAME

NM=4 NL=0 NSEC=0

1 SH=R T=.1,3 E=29000 G=11154 W=0.0026352 M=6.8391E-07 TC=0
 2 SH=R T=5.487,0.477 E=1711 G=106.9 W=8.1764E-05 M=2.1114E-07 TC=0
 3 SH=R T=16,5 E=0.119 G=0.00417 W=0.00018584 M=4.8128E-06 TC=0
 4 SH=R T=3,3 E=.121 G=0.00417 W=3.477E-08 M=9E-11 TC=0
 1 1 2 M=2,2,1 LP=1,0 MS= 0,0
 2 2 3 M=2,2,1 LP=1,0 MS= 0,0
 3 3 4 M=2,2,1 LP=1,0 MS= 0,0
 4 4 5 M=2,2,1 LP=1,0 MS= 0,0
 5 5 6 M=2,2,1 LP=1,0 MS= 0,0
 6 6 7 M=2,2,1 LP=1,0 MS= 0,0
 7 7 8 M=2,2,1 LP=1,0 MS= 0,0
 8 8 9 M=2,2,1 LP=1,0 MS= 0,0

9 9 10 M=2,2,1 LP=1,0 MS= 0,0
 10 10 11 M=2,2,1 LP=1,0 MS= 0,0
 11 11 12 M=2,2,1 LP=1,0 MS= 0,0
 12 12 13 M=2,2,1 LP=1,0 MS= 0,0
 13 13 14 M=2,2,1 LP=1,0 MS= 0,0
 14 5 100 M=3,3,1 LP=1,0 MS= 0,0
 15 10 101 M=3,3,1 LP=1,0 MS= 0,0
 116 100 201 M=4,4,1 LP=1,0 MS= 0,0
 117 101 204 M=4,4,1 LP=1,0 MS= 0,0
 118 200 201 M=1,1,1 LP=1,0 MS= 0,0
 119 201 202 M=1,1,1 LP=1,0 MS= 0,0
 120 203 204 M=1,1,1 LP=1,0 MS= 0,0
 121 204 205 M=1,1,1 LP=1,0 MS= 0,0
 216 201 301 M=4,4,1 LP=1,0 MS= 0,0
 217 204 304 M=4,4,1 LP=1,0 MS= 0,0
 218 300 301 M=1,1,1 LP=1,0 MS= 0,0
 219 301 302 M=1,1,1 LP=1,0 MS= 0,0
 220 303 304 M=1,1,1 LP=1,0 MS= 0,0
 221 304 305 M=1,1,1 LP=1,0 MS= 0,0
 316 301 401 M=4,4,1 LP=1,0 MS= 0,0
 317 304 404 M=4,4,1 LP=1,0 MS= 0,0
 318 400 401 M=1,1,1 LP=1,0 MS= 0,0
 319 401 402 M=1,1,1 LP=1,0 MS= 0,0
 320 403 404 M=1,1,1 LP=1,0 MS= 0,0
 321 404 405 M=1,1,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=0,1,0,1,0,1
 2 2 1 R=0,1,0,1,0,1
 3 3 1 R=0,1,0,1,0,1
 4 4 1 R=0,1,0,1,0,1
 5 5 1 R=0,1,0,1,0,1
 6 6 1 R=0,1,0,1,0,1
 7 7 1 R=0,1,0,1,0,1
 8 8 1 R=0,1,0,1,0,1

9 9 1 R=0,1,0,1,0,1
10 10 1 R=0,1,0,1,0,1
11 11 1 R=0,1,0,1,0,1
12 12 1 R=0,1,0,1,0,1
13 13 1 R=0,1,0,1,0,1
14 14 1 R=0,1,0,1,0,1
100 100 1 R=0,1,0,1,0,1
101 101 1 R=0,1,0,1,0,1
200 200 1 R=0,1,0,1,0,1
201 201 1 R=0,1,0,1,0,1
202 202 1 R=0,1,0,1,0,1
203 203 1 R=0,1,0,1,0,1
204 204 1 R=0,1,0,1,0,1
205 205 1 R=0,1,0,1,0,1
300 300 1 R=0,1,0,1,0,1
301 301 1 R=0,1,0,1,0,1
302 302 1 R=0,1,0,1,0,1
303 303 1 R=0,1,0,1,0,1
304 304 1 R=0,1,0,1,0,1
305 305 1 R=0,1,0,1,0,1
400 400 1 R=0,1,0,1,0,1
401 401 1 R=0,1,0,1,0,1
402 402 1 R=0,1,0,1,0,1
403 403 1 R=0,1,0,1,0,1
404 404 1 R=0,1,0,1,0,1
405 405 1 R=0,1,0,1,0,1

SPRINGS

1 1 1 K=0.1,0,24.1,0,0,0
14 14 1 K=0.1,0,24.1,0,0,0
4 4 1 K=0,0,38.7,0,0,0
6 6 1 K=0,0,38.7,0,0,0
9 9 1 K=0,0,38.7,0,0,0
11 11 1 K=0,0,38.7,0,0,0
2 2 1 K=0,0,35,0,0,0
3 3 1 K=0,0,35,0,0,0

```

7 7 1 K=0,0,35,0,0,0
8 8 1 K=0,0,35,0,0,0
12 12 1 K=0,0,35,0,0,0
13 13 1 K=0,0,35,0,0,0

```

Output file

```

C S I / S A P 9 0 - - F I N I T E   E L E M E N T   A N A L Y S I S   O F   S T R U C T U R E S
P A G E       2

```

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PROGRAM:SAP90/FILE:3apple.RIT
2 span model with 275# c-flute, column of apples

```

E I G E N V A L U E S A N D F R E Q U E N C I E S

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.544739E+03	.233396E+02	3.714619	.269207
2	.560981E+03	.236850E+02	3.769590	.265281
3	.518797E+04	.720275E+02	11.463538	.087233
4	.194575E+05	.139490E+03	22.200559	.045044
5	.307259E+05	.175288E+03	27.897970	.035845

C 4.0 Results

The detailed results of the RoPUL model can be found in the output files below.

In each case Mode number 5 on the output corresponds to the first vertical mode for comparison to the vibration test results. The results of RoPUL model show good correlation with the natural frequency from the vibration test. From the RoPUL model the expected natural frequency of the stacked loads were 58.3 Hz, 37.8 Hz, and 27.9 Hz for a stack of one, two, and three apples respectively. The vibration test results show the actual natural frequency of the stacks to be 57 Hz, 39 Hz, and 28 Hz for a stack of one, two, and three apples respectively.

Appendix D. Using natural frequency to determine the effective stiffness of corrugated board for input into the RoPUL model

D 1.0 Introduction

Using the spring-mass system analog, the bottom of the corrugated container can be viewed as a spring supporting the product. In RoPUL it is represented as a vertical frame element (a column) supporting the product model. Cushioning materials like corrugated fiberboard tend to have nonlinear load-deformation characteristics. As the material is compressed either by a heavier load or the same load applied more quickly the material is densified and becomes stiffer. To represent them within RoPUL with a frame element with linear elastic properties it is necessary to determine the stiffness of the corrugated fiberboard at the expected load level. To confirm the suitability of using equation 7 to determining the corrugated board stiffness values for the RoPUL model, vibration testing was done on a 275 lb. c-flute board at three different levels of loading.

D 2.0 Methods

From a single sheet of corrugated board ten 16-inch by 6-inch samples were cut. For the first test a 16-inch by 6-inch steel plate weighing 20.2 lb was placed on each sample in turn. The sample was then subjected to a vibration test sweeping from 5 hertz to 200 hertz. The point of maximum acceleration was used to determine the natural frequency of the loaded corrugated board. The test was then repeated using a 30 lb and a 40.2 lb weight. Equation 7 was then

used to determine the effective stiffness of the corrugated board at each load level. For each loading level SAP90 was used to create a RoPUL model of the corrugated board supporting the steel mass. The RoPUL input files are listed in section D 4.0. The RoPUL models were then used to predict the natural frequency of the system. The output files from the RoPUL simulations are found in Section D 5.0. Results of the RoPUL simulation and the vibration test were then compared.

D 3.0 Results of corrugated board test

The results of the test are shown in Table D 1. As would be expected as the load increased on the corrugated board the natural frequency of the system decreases.

Table D 1. Results of 275 lb C-flute vibration test

Sample	20.2 lb load (Hz)	30 lb load (Hz)	40.2 lb load (Hz)
B1E1P1	115.5	113.6	112.1
B1E1P3	116.2	113.8	112.4
B1E1P5	115.9	114	111.7
B1M1P1	116.3	113.8	110.2
B1M1P3	115.9	113.7	110.7
B1M1P5	115.9	113.5	113.5
B1M2P1	116.0	113.5	109.8
B1M2P3	116.7	113.7	109.8
B1E2P1	116.1	114.4	111.1
B1E2P3	116.4	115.8	111.1
Avg	116.1	114.0	111.2
Std	0.34	0.69	1.20

Using equation 7 the average natural frequency of each loading configuration was used to calculate the effective stiffness of the corrugated column supporting the steel mass. For the 20.2 pound mass the natural frequency of 116.1 hertz corresponds to an effective stiffness of 50.33 psi. For the 30.0 pound mass the natural frequency of 114.1 hertz corresponds to an effective stiffness of 72.32 psi. For the 40 pound mass the natural frequency of 111.2 hertz corresponds to an effective stiffness of 92.05 psi. These values were input into the RoPUL model as the corrugated boards modulus of elasticity. The results of the RoPUL simulations were then compared to the vibration test results.

Table D 2. Comparison of the measured and predicted natural frequency of corrugated board supporting a steel mass

Load Lb	Measured natural freq. Hz	RoPUL natural freq. Hz
20.2	116	115.8
30	114	113.9
40.2	111	111.1

D 4.0 RoPUL input files for the corrugated board simulation

D 4.1 RoPUL input file for the 20 pound load model

C This is file 275c20 written by SAPIN on Sun Oct 16 12:49:24 1994

C Units are KIP INCHES

C model of 275 # c-flute corrugated board with a steel plate mass

C corrugated modeled as a column in compression

C effective modulus of the corrugated column calc from its F_n

C $W_n = AE/ml$

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=52 YN=1 ZN=13

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51

0

0 1 2 3 4 5 6 7

8 9 10 11 12

JOINTS

1 X=4 Y=0 Z=2

2 X=6 Y=0 Z=2

3 X=8 Y=0 Z=2

4 X=10 Y=0 Z=2

5 X=12 Y=0 Z=2

6 X=14 Y=0 Z=2

7 X=16 Y=0 Z=2

8 X=18 Y=0 Z=2

101 X=4 Y=0 Z=2.174

102 X=6 Y=0 Z=2.174

103 X=8 Y=0 Z=2.174

104 X=10 Y=0 Z=2.174

105 X=12 Y=0 Z=2.174

106 X=14 Y=0 Z=2.174

107 X=16 Y=0 Z=2.174

108 X=18 Y=0 Z=2.174

109 X=19 Y=0 Z=2.174

110 X=3 Y=0 Z=2.174

FRAME

NM=2 NL=0 NSEC=0

1 SH=R T=0.75,6 E=29000 G=11154 W=0.0012625 M=3.267E-06 TC=8.3E-06

2 SH=R T=2,6 E=0.05033 G=0.049982 W=8.7082E-05 M=2.2536E-07 TC=0

1 110 101 M=1,1,1 LP=1,0 MS= 0,0

2 101 102 M=1,1,1 LP=1,0 MS= 0,0

3 102 103 M=1,1,1 LP=1,0 MS= 0,0

4 103 104 M=1,1,1 LP=1,0 MS= 0,0

5 104 105 M=1,1,1 LP=1,0 MS= 0,0

6 105 106 M=1,1,1 LP=1,0 MS= 0,0

7 106 107 M=1,1,1 LP=1,0 MS= 0,0

8 107 108 M=1,1,1 LP=1,0 MS= 0,0

9 108 109 M=1,1,1 LP=1,0 MS= 0,0

10 1 101 M=2,2,1 LP=1,0 MS= 0,0

11 2 102 M=2,2,1 LP=1,0 MS= 0,0

12 3 103 M=2,2,1 LP=1,0 MS= 0,0

13 4 104 M=2,2,1 LP=1,0 MS= 0,0

14 5 105 M=2,2,1 LP=1,0 MS= 0,0

15 6 106 M=2,2,1 LP=1,0 MS= 0,0

16 7 107 M=2,2,1 LP=1,0 MS= 0,0

17 8 108 M=2,2,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=1,1,1,1,0,1

2 2 1 R=1,1,1,1,0,1

3 3 1 R=1,1,1,1,0,1

4 4 1 R=1,1,1,1,0,1

5 5 1 R=1,1,1,1,0,1

6 6 1 R=1,1,1,1,0,1

7 7 1 R=1,1,1,1,0,1

8 8 1 R=1,1,1,1,0,1

101 101 1 R=1,1,0,1,0,1

102 102 1 R=1,1,0,1,0,1

103 103 1 R=1,1,0,1,0,1

104 104 1 R=1,1,0,1,0,1
105 105 1 R=1,1,0,1,0,1
106 106 1 R=1,1,0,1,0,1
107 107 1 R=1,1,0,1,0,1
108 108 1 R=1,1,0,1,0,1
109 109 1 R=1,1,0,1,0,1
110 110 1 R=1,1,0,1,0,1

D 4.2 RoPUL input file for the 30 pound load model

C This is file 275c30 written by SAPIN on Sun Oct 16 12:49:24 1994
C Units are KIP INCHES
C model of 275 # c-flute corrugated board with a 30# steel plate mass
C corrugated modeled as a column in compression
C effective modulus of the corrugated column calc from its F_n
C $W_n = AE/ml$

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=52 YN=1 ZN=13

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51

0

0 1 2 3 4 5 6 7

8 9 10 11 12

JOINTS

1 X=4 Y=0 Z=2
2 X=6 Y=0 Z=2
3 X=8 Y=0 Z=2
4 X=10 Y=0 Z=2
5 X=12 Y=0 Z=2
6 X=14 Y=0 Z=2
7 X=16 Y=0 Z=2
8 X=18 Y=0 Z=2
101 X=4 Y=0 Z=2.174
102 X=6 Y=0 Z=2.174
103 X=8 Y=0 Z=2.174
104 X=10 Y=0 Z=2.174
105 X=12 Y=0 Z=2.174
106 X=14 Y=0 Z=2.174
107 X=16 Y=0 Z=2.174
108 X=18 Y=0 Z=2.174
109 X=19 Y=0 Z=2.174
110 X=3 Y=0 Z=2.174

FRAME

NM=2 NL=0 NSEC=0

1 SH=R T=0.75,6 E=29000 G=11154 W=0.001875 M=4.852E-06 TC=0
2 SH=R T=2,6 E=0.07232579 G=0.049982 W=8.7082E-05 M=2.2536E-07 TC=0
1 110 101 M=1,1,1 LP=1,0 MS= 0,0
2 101 102 M=1,1,1 LP=1,0 MS= 0,0
3 102 103 M=1,1,1 LP=1,0 MS= 0,0
4 103 104 M=1,1,1 LP=1,0 MS= 0,0
5 104 105 M=1,1,1 LP=1,0 MS= 0,0
6 105 106 M=1,1,1 LP=1,0 MS= 0,0
7 106 107 M=1,1,1 LP=1,0 MS= 0,0
8 107 108 M=1,1,1 LP=1,0 MS= 0,0
9 108 109 M=1,1,1 LP=1,0 MS= 0,0
10 1 101 M=2,2,1 LP=1,0 MS= 0,0
11 2 102 M=2,2,1 LP=1,0 MS= 0,0
12 3 103 M=2,2,1 LP=1,0 MS= 0,0
13 4 104 M=2,2,1 LP=1,0 MS= 0,0

14 5 105 M=2,2,1 LP=1,0 MS= 0,0
15 6 106 M=2,2,1 LP=1,0 MS= 0,0
16 7 107 M=2,2,1 LP=1,0 MS= 0,0
17 8 108 M=2,2,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=1,1,1,1,0,1
2 2 1 R=1,1,1,1,0,1
3 3 1 R=1,1,1,1,0,1
4 4 1 R=1,1,1,1,0,1
5 5 1 R=1,1,1,1,0,1
6 6 1 R=1,1,1,1,0,1
7 7 1 R=1,1,1,1,0,1
8 8 1 R=1,1,1,1,0,1
101 101 1 R=1,1,0,1,0,1
102 102 1 R=1,1,0,1,0,1
103 103 1 R=1,1,0,1,0,1
104 104 1 R=1,1,0,1,0,1
105 105 1 R=1,1,0,1,0,1
106 106 1 R=1,1,0,1,0,1
107 107 1 R=1,1,0,1,0,1
108 108 1 R=1,1,0,1,0,1
109 109 1 R=1,1,0,1,0,1
110 110 1 R=1,1,0,1,0,1

D 4.3 RoPUL input file for the 40 pound load model

C This is file 275c40 written by SAPIN on Sun Oct 16 12:49:24 1994

C Units are KIP INCHES

C model of 275 # c-flute corrugated board with a 40.2# steel plate mass

C corrugated modeled as a column in compression

C effective modulus of the corrugated column calc from its Fn

C Wn = AE/ml

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=52 YN=1 ZN=13

0 1 2 3 4 5 6 7

8 9 10 11 12 13 14 15

16 17 18 19 20 21 22 23

24 25 26 27 28 29 30 31

32 33 34 35 36 37 38 39

40 41 42 43 44 45 46 47

48 49 50 51

0

0 1 2 3 4 5 6 7

8 9 10 11 12

JOINTS

1 X=4 Y=0 Z=2

2 X=6 Y=0 Z=2

3 X=8 Y=0 Z=2

4 X=10 Y=0 Z=2

5 X=12 Y=0 Z=2

6 X=14 Y=0 Z=2

7 X=16 Y=0 Z=2

8 X=18 Y=0 Z=2

101 X=4 Y=0 Z=2.174

102 X=6 Y=0 Z=2.174

103 X=8 Y=0 Z=2.174

104 X=10 Y=0 Z=2.174

105 X=12 Y=0 Z=2.174

106 X=14 Y=0 Z=2.174

107 X=16 Y=0 Z=2.174

108 X=18 Y=0 Z=2.174

109 X=19 Y=0 Z=2.174

110 X=3 Y=0 Z=2.174

FRAME

NM=2 NL=0 NSEC=0

1 SH=R T=0.75,6 E=29000 G=11154 W=0.0025125 M=6.502E-06 TC=0

2 SH=R T=2,6 E=0.09205264 G=0.049982 W=8.7082E-05 M=2.2536E-07 TC=0

1 110 101 M=1,1,1 LP=1,0 MS= 0,0

2 101 102 M=1,1,1 LP=1,0 MS= 0,0

3 102 103 M=1,1,1 LP=1,0 MS= 0,0

4 103 104 M=1,1,1 LP=1,0 MS= 0,0

5 104 105 M=1,1,1 LP=1,0 MS= 0,0

6 105 106 M=1,1,1 LP=1,0 MS= 0,0

7 106 107 M=1,1,1 LP=1,0 MS= 0,0

8 107 108 M=1,1,1 LP=1,0 MS= 0,0

9 108 109 M=1,1,1 LP=1,0 MS= 0,0

10 1 101 M=2,2,1 LP=1,0 MS= 0,0

11 2 102 M=2,2,1 LP=1,0 MS= 0,0

12 3 103 M=2,2,1 LP=1,0 MS= 0,0

13 4 104 M=2,2,1 LP=1,0 MS= 0,0

14 5 105 M=2,2,1 LP=1,0 MS= 0,0

15 6 106 M=2,2,1 LP=1,0 MS= 0,0

16 7 107 M=2,2,1 LP=1,0 MS= 0,0

17 8 108 M=2,2,1 LP=1,0 MS= 0,0

RESTRAINTS

1 1 1 R=1,1,1,1,0,1

2 2 1 R=1,1,1,1,0,1

3 3 1 R=1,1,1,1,0,1

4 4 1 R=1,1,1,1,0,1

5 5 1 R=1,1,1,1,0,1

6 6 1 R=1,1,1,1,0,1

7 7 1 R=1,1,1,1,0,1

8 8 1 R=1,1,1,1,0,1

101 101 1 R=1,1,0,1,0,1

102 102 1 R=1,1,0,1,0,1

103 103 1 R=1,1,0,1,0,1

104 104 1 R=1,1,0,1,0,1

105 105 1 R=1,1,0,1,0,1

106 106 1 R=1,1,0,1,0,1

107 107 1 R=1,1,0,1,0,1

108 108 1 R=1,1,0,1,0,1

109 109 1 R=1,1,0,1,0,1

110 110 1 R=1,1,0,1,0,1

D 5.0 RoPUL output files for the corrugated board simulation

D 5.1 RoPUL output file for the 20 pound load model

CSI / SAP90 - - FINITE ELEMENT ANALYSIS OF STRUCTURES PAGE 2
PROGRAM:SAP90/FILE:275c20.RIT

EIGENVALUES AND FREQUENCIES

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.507655E+06	.712499E+03	113.397806	.008819
2	.529636E+06	.727761E+03	115.826769	.008634
3	.587179E+09	.242318E+05	3856.607263	.000259
4	.478346E+10	.691626E+05	11007.566145	.000091
5	.145121E+11	.120466E+06	19172.806032	.000052

D 5.2 RoPUL output file for the 30 pound load model

CSI / SAP90 - - FINITE ELEMENT ANALYSIS OF STRUCTURES PAGE 2
PROGRAM:SAP90/FILE:275c30.RIT

EIGENVALUES AND FREQUENCIES

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.491494E+06	.701066E+03	111.578160	.008962
2	.512975E+06	.716223E+03	113.990417	.008773
3	.395863E+09	.198963E+05	3166.595500	.000316
4	.322390E+10	.567794E+05	9036.726075	.000111
5	.978066E+10	.988972E+05	15739.980673	.000064

D 5.3 RoPUL output file for the 40 pound load model

CSI / SAP90 - - FINITE ELEMENT ANALYSIS OF STRUCTURES PAGE 2

PROGRAM:SAP90/FILE:275c40.RIT

EIGENVALUES AND FREQUENCIES

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.466952E+06	.683339E+03	108.756722	.009195
2	.487456E+06	.698180E+03	111.118848	.008999
3	.295640E+09	.171942E+05	2736.539132	.000365
4	.240701E+10	.490613E+05	7808.350728	.000128
5	.730238E+10	.854540E+05	13600.422466	.000074

Appendix E SAP90 input files for bending moment test

E 1.0 Center point loading model

C This is file for the center point loading model for the bending moment test written by SAPIN on
Tue Apr 14 14:39:34 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=14 YN=1 ZN=4

0 1 2 3 4 5 6 7

8 9 10 11 12 13

0

0 1 2 3

JOINTS

1 X=2 Y=0 Z=2

2 X=3 Y=0 Z=2

3 X=4 Y=0 Z=2

4 X=5 Y=0 Z=2

5 X=6 Y=0 Z=2

6 X=7 Y=0 Z=2

7 X=8 Y=0 Z=2

8 X=9 Y=0 Z=2

9 X=10 Y=0 Z=2

10 X=11 Y=0 Z=2

100 x=6.495 y=0 z=2

101 x=6.505 y=0 z=2

FRAME

NM=3 NL=1 NSEC=0

1 SH=R T=1,1 E=1000 G=100 W=0.0001 M=2.59E-07 TC=0

2 SH=R T=1,1 E=1000 G=100 W=0.0534 M=0.0001382 TC=0

3 SH=R T=1,1 E=1000 G=100 W=13.333 M=0.034507 TC=0

1 1 2 M=1,1,1 LP=0,0 MS= 0,0

2 2 3 M=1,1,1 LP=0,0 MS= 0,0
 3 3 4 M=1,1,1 LP=0,0 MS= 0,0
 11 4 5 M=1,1,1 LP=0,0 MS= 0,0
 13 5 100 M=1,1,1 LP=0,0 MS= 0,0
 15 100 101 M=3,3,1 LP=0,0 MS= 0,0
 14 101 6 M=1,1,1 LP=0,0 MS= 0,0
 12 6 7 M=1,1,1 LP=0,0 MS= 0,0
 7 7 8 M=1,1,1 LP=0,0 MS= 0,0
 8 8 9 M=1,1,1 LP=0,0 MS= 0,0
 9 9 10 M=1,1,1 LP=0,0 MS= 0,0

RESTRAINTS

1 1 1 R=1,1,1,1,0,1
 2 2 1 R=0,1,0,1,0,1
 3 3 1 R=0,1,0,1,0,1
 4 4 1 R=0,1,0,1,0,1
 5 5 1 R=0,1,0,1,0,1
 6 6 1 R=0,1,0,1,0,1
 7 7 1 R=0,1,0,1,0,1
 8 8 1 R=0,1,0,1,0,1
 9 9 1 R=0,1,0,1,0,1
 10 10 1 R=1,1,1,1,0,1
 100 100 1 R=0,1,0,1,0,1
 101 101 1 R=0,1,0,1,0,1

E 2.0 Middle third loading model

C This is file Middle third loading for the bending moment test written by SAPIN on Tue Apr 14
 14:39:34 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=5

GRID

XN=14 YN=1 ZN=4

0 1 2 3 4 5 6 7
8 9 10 11 12 13

0

0 1 2 3

JOINTS

1 X=2 Y=0 Z=2
2 X=3 Y=0 Z=2
3 X=4 Y=0 Z=2
4 X=5 Y=0 Z=2
5 X=6 Y=0 Z=2
6 X=7 Y=0 Z=2
7 X=8 Y=0 Z=2
8 X=9 Y=0 Z=2
9 X=10 Y=0 Z=2
10 X=11 Y=0 Z=2

FRAME

NM=3 NL=1 NSEC=0

1 SH=R T=1,1 E=1000 G=100 W=0.0001 M=2.59E-07 TC=0
2 SH=R T=1,1 E=1000 G=100 W=0.0534 M=0.0001382 TC=0
3 SH=R T=1,1 E=1000 G=100 W=13.333 M=0.034507 TC=0
1 WL=0,0,0 WG=0,0,0.267 T=0,0,0
1 1 2 M=1,1,1 LP=0,0 MS= 0,0
2 2 3 M=1,1,1 LP=0,0 MS= 0,0
3 3 4 M=1,1,1 LP=0,0 MS= 0,0
4 4 5 M=2,2,1 LP=0,0 MS= 0,0
5 5 6 M=2,2,1 LP=0,0 MS= 0,0
6 6 7 M=2,2,1 LP=0,0 MS= 0,0
7 7 8 M=1,1,1 LP=0,0 MS= 0,0
8 8 9 M=1,1,1 LP=0,0 MS= 0,0
9 9 10 M=1,1,1 LP=0,0 MS= 0,0

RESTRAINTS

1 1 1 R=1,1,1,1,0,1
10 10 1 R=1,1,1,1,0,1
2 2 1 R=0,1,0,1,0,1
3 3 1 R=0,1,0,1,0,1

4 4 1 R=0,1,0,1,0,1
5 5 1 R=0,1,0,1,0,1
6 6 1 R=0,1,0,1,0,1
7 7 1 R=0,1,0,1,0,1
8 8 1 R=0,1,0,1,0,1
9 9 1 R=0,1,0,1,0,1

E 3.0 Uniformly distributed load model

C This is file for the Uniformly distributed load model for the bending moment test written by
SAPIN on Tue Apr 14 14:38:34 1998

C Units are KIP INCHES

SYSTEM

R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=4

GRID

XN=14 YN=1 ZN=4

0 1 2 3 4 5 6 7

8 9 10 11 12 13

0

0 1 2 3

JOINTS

1 X=2 Y=0 Z=2

2 X=3 Y=0 Z=2

3 X=4 Y=0 Z=2

4 X=5 Y=0 Z=2

5 X=6 Y=0 Z=2

6 X=7 Y=0 Z=2

7 X=8 Y=0 Z=2

8 X=9 Y=0 Z=2

9 X=10 Y=0 Z=2

10 X=11 Y=0 Z=2

FRAME

NM=1 NL=1 NSEC=0

1 SH=R T=1,1 E=1000 G=100 W=0.0001 M=2.59E-07 TC=0
 1 WL=0,0,0 WG=0,0,-0.029667 T=0,0,0
 1 1 2 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 2 2 3 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 3 3 4 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 4 4 5 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 5 5 6 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 6 6 7 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 7 7 8 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 8 8 9 M=1,1,1 LP=0,0 MS= 0,0 NSL=1
 9 9 10 M=1,1,1 LP=0,0 MS= 0,0 NSL=1

RESTRAINTS

1 1 1 R=1,1,1,1,0,1
 10 10 1 R=1,1,1,1,0,1
 2 2 1 R=0,1,0,1,0,1
 3 3 1 R=0,1,0,1,0,1
 4 4 1 R=0,1,0,1,0,1
 5 5 1 R=0,1,0,1,0,1
 6 6 1 R=0,1,0,1,0,1
 7 7 1 R=0,1,0,1,0,1
 8 8 1 R=0,1,0,1,0,1
 9 9 1 R=0,1,0,1,0,1

Appendix F User guide to RoPUL

F 1.0 Introduction

The Sap90 series of programs were chosen for use in developing the RoPUL model in part because of their ease of use. The windows based SAPIN Module used for visually building your model is fairly straight forward to use and it is not my intention here to re-write the excellent user manuals for this series of programs but rather to walk the user through a simple input file such as would be built using the SAPIN program. Each section of the file will be described and those sections that would require specific user input will be noted.

F 2.0 RoPUL input files

The file "SIMPLE" is an input file built using the SAPIN module of the SAP90 series of programs. "SIMPLE" is a model of a simply supported steel beam, and it will be used to determine the beams first natural frequency.

The first two line of code (and any line that starts with a C is a comment line)

```
C This is file SIMPLE written by SAPIN on Fri Aug 10 12:54:03 2001
```

```
C Units are KIP INCHES
```

The system block contains job control information. It tells SAP90 what type of analysis to perform on the file. In this case the L=1 indicates one loading condition, and Z=1 indicates that we would like to determine the first mode of vibration of the model

```
SYSTEM
```

```
R=0 L=1 C=0 V=0 T=0.0001 P=0 W=0 Z=1
```

The grid block the space within which the model was constructed in this case it is a two-dimensional model (in the x-z plane) 14 inches in the x direction and 4 inches in the z direction. This grid is used to reference the location of components of the model.

GRID

XN=14 YN=1 ZN=4

The x –axis has 14 evenly spaced grid references.

0 1 2 3 4 5 6 7

8 9 10 11 12 13

The y-axis is a zero length axis.

0

The z-axis has 4 evenly spaced grid references.

0 1 2 3

The joints block list the coordinates of all the joints in the model, referenced by their grid location.

JOINTS

1 X=2 Y=0 Z=2

2 X=3 Y=0 Z=2

3 X=4 Y=0 Z=2

4 X=5 Y=0 Z=2

5 X=6 Y=0 Z=2

6 X=7 Y=0 Z=2

7 X=8 Y=0 Z=2

8 X=9 Y=0 Z=2

9 X=10 Y=0 Z=2

10 X=11 Y=0 Z=2

The Frame block list frame element data.

FRAME

The first line is control information the NM=1 indicates there is only one material property listed in the next section.

NM=1 NL=0 NSEC=0

The next line contains the material property information for the frame element used in the model. Sh=R indicates the cross-section is rectangular, T=1,1 indicates the rectangle is 1-inch by 1-inch, E=1000 is the materials modulus of elasticity, G= is the materials Shear modulus, W= is the materials weight per unit length (used for static analysis), M= is the materials mass per unit length (used in dynamic analysis). Both the weight and mass are calculated for you by SAPIN from a user input density value. TC= is a thermal expansion coefficient

1 SH=R T=1,1 E=1000 G=100 W=0.0001 M=2.59E-07 TC=0

The next section contains the frame element location data. The format is Frame identification number, Joint number at end 1, joint number at end 2, M= material

property at end 1, material property at end 2, the type of transition between end 1 and end 2, LP= describe the joint number defining the local axis, and MS= defines the global axis

```

1  1  2  M=1,1,1 LP=0,0 MS= 0,0
2  2  3  M=1,1,1 LP=0,0 MS= 0,0
3  3  4  M=1,1,1 LP=0,0 MS= 0,0
4  4  5  M=1,1,1 LP=0,0 MS= 0,0
5  5  6  M=1,1,1 LP=0,0 MS= 0,0
6  6  7  M=1,1,1 LP=0,0 MS= 0,0
7  7  8  M=1,1,1 LP=0,0 MS= 0,0
8  8  9  M=1,1,1 LP=0,0 MS= 0,0
9  9 10  M=1,1,1 LP=0,0 MS= 0,0

```

Restraints block contains information on joint restraints. The format is beginning joint number, ending joint number, increment (used to define multiple joints with the same restraint), R=x-translation, y-translation, z-translation, x-rotation, y-rotation, z-rotation. A 1 indicates that movement in that direction is restrained and a 0 indicates unrestrained movement in that direction.

RESTRAINTS

Joint 1 and 10 are the endpoints of our simply supported beam as such they are "pinned" joints restrained from all translational movement, and since our model is only in the x-z plane it is also restrained from out of plane rotation, but is free to rotate around the y-axis.

```

1  1  1  R=1,1,1,1,0,1
10 10 1  R=1,1,1,1,0,1

```

All other joints are free to move translationally within the x-z plane and rotate about the y-axis.

```

2  2  1  R=0,1,0,1,0,1
3  3  1  R=0,1,0,1,0,1
4  4  1  R=0,1,0,1,0,1
5  5  1  R=0,1,0,1,0,1
6  6  1  R=0,1,0,1,0,1
7  7  1  R=0,1,0,1,0,1
8  8  1  R=0,1,0,1,0,1
9  9  1  R=0,1,0,1,0,1

```

Since most of the RoPUL models do not have rigidly fixed they also contain a "springs" block with the same format as the restraints block, substituting a spring constant for each of the restraint codes.

F 3.0 RoPUL (.RIT) output file

Since RoPUL is intended to be used to determine the natural frequency of the model it is the SAP90 .rit file that is of interest. Below is a portion of the Simple.rit file generated by SAP90 using the above input file.

```
C S I / S A P 9 0 - - FINITE ELEMENT ANALYSIS OF STRUCTURES  
PAGE      2
```

```
PROGRAM:SAP90/FILE:simple.RIT
```

In this section is provided information on the frequencies of the modes requested in the input file. In this case only the first mode is described which is vibrating at 328.23 hertz.

```
E I G E N V A L U E S      A N D      F R E Q U E N C I E S
```

MODE NUMBER	EIGENVALUE (RAD/SEC)**2	CIRCULAR FREQ (RAD/SEC)	FREQUENCY (CYCLES/SEC)	PERIOD (SEC)
1	.425330E+07	.206235E+04	328.233521	.003047

F 4.0 Saplot output for the “simple”model

In addition to the information provide in the out-put text files generated by SAP90 the program also contains a graphical interface program called SAPLOT which will allow the user to view graphically the information provided in the text files.

Figure F 1 is an example of the graphical representation of the first mode of vibration of the “Simple” model.

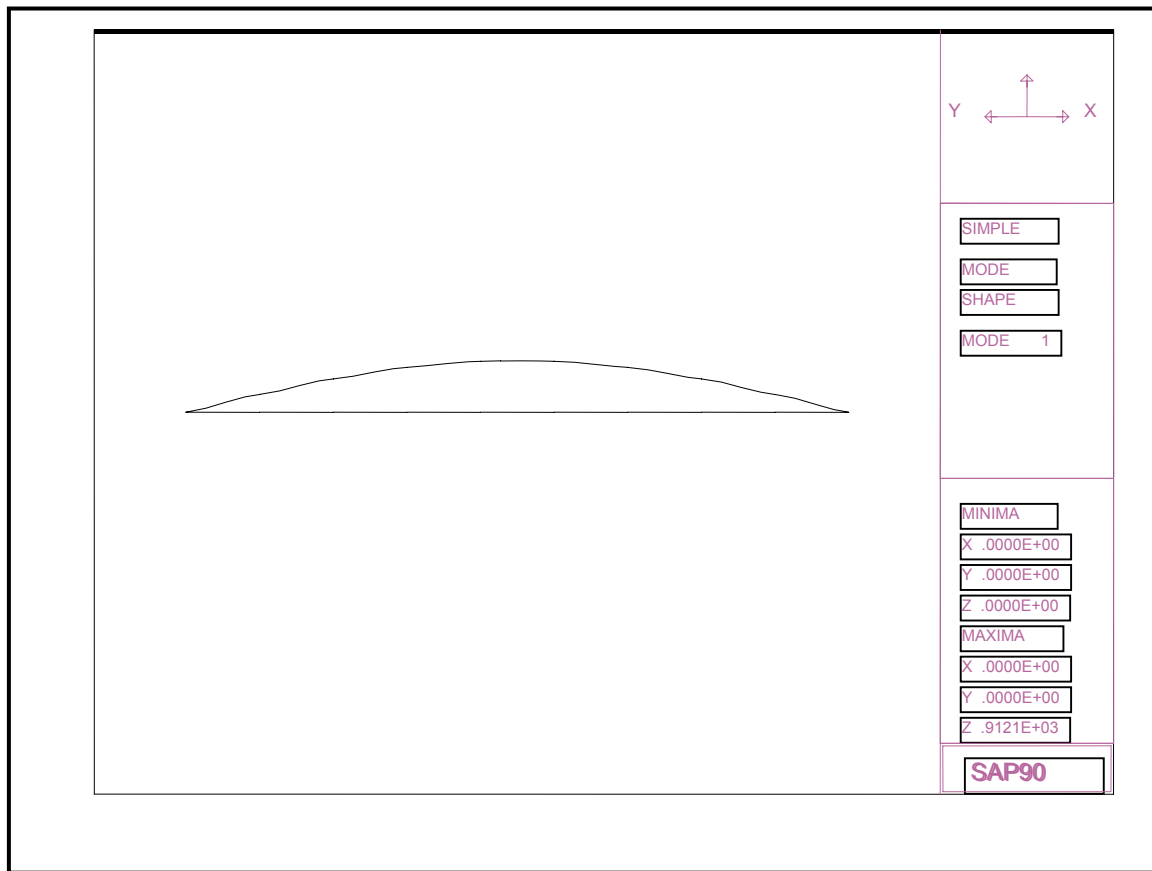


Figure F1. Saplot graphical output of “simple’s” first mode

F 5.0 User inputs into the RoPUL model

The idea behind RoPUL is to let user simulate a variety of unit load configurations to determine which is most likely to protect the product from vibration induced damage. To this end the user must know the mechanical properties of the material involved in building the unit load, pallet components, corrugated board properties, and the properties of the product. These include all the information needed by SAP90 to describe the frame elements used to simulate the various components. Including the materials modulus of elasticity, its shear modulus, density, and size. Equally important is knowledge of any connection between components, for example the stiffness of the pallet joints is entered into the program as a series of springs restraining the deck-board frame element. Once these characteristics are entered into the program using SAPIN, and an input file is generated the user can change the model either by returning to SAPIN to edit the file or they can access the text file and modify it with any text editor. For example it would be a simple process to access the text file and modify the Frame section of the input file to look at the effect of using thinner deck-board, or changing to a stiffer material for the pallet.

Vita

The author originally from Lansing, Michigan received his Bachelor degree in Packaging Science from Michigan State University in 1984. After a three-year stint in the military he returned to Michigan to pursue graduate studies in wood science and packaging. He received a Master of Science in Wood Science from Michigan State University in 1992 and a Master of Science in Packaging Science from Michigan State University in 1996. He began his doctoral program in Wood Science at Virginia Polytechnic Institute and State University in January of 1994. Since November of 1999 he has been employed as an Assistant Professor in the departments of Packaging Science and Forest Resource at Clemson University.