Forest Products Laboratory

RESEARCH REPORT

Grading of Round Timbers For Use In Bending

Performed in the degree course
Forest Products Technology and Timber Construction
at the Universtiy of Applied Sciences Salzburg

Research conducted at
The Forest Products Laboratory
and
Whole Trees Architecture and Structures

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Kuchl, on the 15th of December 2016

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List of Abbreviations

ASTM - American Society for Testing and Materials

COV – Coefficient of Variability

CNR – US House of Representatives Committee on Natural Resources

DNR – Department of Natural Resources

LSA – Life Cycle Assessment

LVDT – Lineal Variable Differential Transformer

MG – Machine Grading

MOE – Modulus of Elasticity

MOR – Modulus of Rupture

MSG – Machine Stress Grading

NDE – Non-Destructive Evaluation

SBIR – Small Business Innovation Research Program

SDRT – Small-Diameter Round Timber

WT – Whole Trees Architecture and Structures

Abstract

1 Introduction

1.1 Scope of this Report

This is a report on an ongoing collaborative research project between the Forest Products Laboratory and Whole Trees Architecture & Structures as part of a USDA, Phase I Small Business Innovation Research Grant. Due to resource restraints, destructive testing which was initially planned for August was not completed before the end of my stay in the USA. It is currently scheduled to be conducted at the end of Januray 2017. Therefore this report focuses on the aims and methodology of the project, the results obtained through the end of my stay in the US, and a discussion of the steps and anticipated outcomes of what will follow once destructive testing is completed.

1.2 Background

The commercial project partner in this project, WholeTrees ® Architecture & Structures (WT), is in the process of creating a line of round timber structural systems, derived from forest cullings and engineered for use by the non-residential construction industry. Their aim is to create innovative technologies and designs, which satisfy structural and technical requirements while aligning the needs of forest managers and the “greening” construction industry.

In order to achieve wider market acceptance for their round timber structural systems, they have conducted several research projects with the Forest Products Laboratory over the past 4 years which will help them streamline their processes and imporve efficiency. All projects have the ultimate aim of establishing standards to facilitate widespread use of round timber structural systems.

This project, which is primarily funded through a small business innovation research grant, focuses on using metrics which can be gathered from round timbers in the supply chain using non-destructive evaluation methods (NDE) to establish a correlation to their actual bending strength.

Generally stated, the aim of this project is to establish improved selection and grading procedures for round timbers that will be used in bending. The ultimate goal is to develop load tables for round timbers which structural engineers can use to stamp structural products, including round timber truss systems, which are based on in-field metrics “green” metrics that correlate to their actual bending strength. This will have 2 major benefits. First, it will allow for improved selection and sorting of round timber early in the supply chain allowing for better resource use and more efficient processes. Secondly, it could potentially reduce structural design values which would lead to even more efficient resource use and help round timber structural systems become more price competitive.

1.3 Statement of Problem

This project addresses problems from several areas and has commercial, technical and environmental implications. Therefore, background regarding specific aspects of the problem are discussed separately in the sections below and summarized in Section 1.3.7.

1.3.1 Round Timber in Construction

Despite being one of the oldest construction materials used by humans and the fact that small diameter round timber (SDRT[1]) is an abundant and rapidly renewable byproduct of well managed forests, there is no optimally accepted means of deriving design values for use in spanning structures. Currently, in order to use spanning round timber members, WT has to work with structural engineers and local code officials to win approval, which typically

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[1] For this project, small-diameter round timber (SDRT) is defined as having a trunk with a diameter of 4-12 inches.

requires significantly overdesigning round timber members and connections. These design values are derived solely from visual grading techniques outlined in ASTM D2899 and ASTM3000, which are procedures for poles and piles loaded axially and cantilevered, and are not intended for spanning members.

In order for WT to gain a larger market share in non-residential projects, they need a cost effective and accurate means of grading round timber with more accuracy. With such a grading system, WT believes increased efficiency and decreased design values would help increase demand for round timber structural systems.

1.3.2 Embodied Energy in Construction Materials

Construction is an energy intensive industry and the embodied energy in building materials (the energy used to extract raw materials, manufactor and transport products) constitutes a large precentage of the energy which is consumed by the average construction project. Reducing the amount of embodied energy in construction materials could help significantly descrease the total amount of energy used in construction.

Life Cycle Assessments have been developed as a tool, in part to measure and minimize energy use in construction. According to one Life Cycle Assessment, WT round timbers require less than a quarter of the energy to produce than an equivalent sized milled lumber structure, and less than an eighth that of recycled steel. WT outperformed lumber, heretofore the Life Cycle Assessment champion, in all Life Cycle Assessment categories until the timbers needed shipping more than a thousand miles (Bratkovich, et al. 2001, Cooke 2011). Efficient round timber selection and grading techniques will reduce energy use and waste in all stages of harvest, processing, manufacturing, and shipping for what is already the industry leader in low-embodied energy.

Utilizing SDRT in structural systems replaces high-embodied energy materials such as steel. Instead of an energy intensive prodcution process common to most building materials, a renewable energy—sunlight— builds much of the structural value of the material and greatly reduces the need to generate energy through other means necessary to create alternative structural materials. Embodied energy in SDRT which is used in construction is limited to that which is required to harvest, process, and transport it. When a SDRT can replace a traditionally high-embodied energy material energy the energy consumption of a building project will be reduced significantly.

1.3.3 Under Managed Forests

Aside from the positive environmental impact SDRT-based structural systems have in the form of decreased energy consumption, an increased market acceptance for SDRT-based construction products would contribute to improved forest management by creating a high-value-added use for forest cullings and encouraging better forestry practices.

A recent U.S. House of Representative Committee on National Resources (CNR) bulletin states that the under-managed “national forests are in an unhealthy and dangerous state (Committee on National Resources, 2013). U.S. Department of Agriculture Secreatary, Tom Vilsack said, “a healthy and prosperous America relies on the health of our natural resources, and particularly its forests” (USDA 2009). SDRT is an under-utilized waste product of well-managed forests. The US has over 700 million acres of private and public forests, a large percentage of which are critically under-managed (Bowyer 2011). In the US, lumber and pulp prices are depressed. The long-term-decline of the housing and paper industries exacerbate overstocking and require diversified markets from the forest products industry. The Department of Natural Resources (DNR) links declining timber harvest with increasing burned acreage and states that “responsible forest management helps prevent catastrophic wildfires.” As Secretary Vilsack encourages, SDRT could serve as a “new opportunity” if emerging markets can be developed.

Higher value added products for SDRT would not only be positive for forests in the US but could also have a positive impact on forest management in many regions throughtout the world. Under-harvested and poorly managed forests exist in many parts of the world. By creating a process to establish grading criteria for round timber based on NDE methods, demand for SDRT - which typically has a low value - could increase significantly which could encourage more efficient forest management in regions where the use of SDRT in construction is adapted on a wider scale.

Additionally, production of round timber structural systems do not require large and expensive manufacturing so production facilities could be set up with a relatively small investment where there is an overstock of SDRT.

1.3.4 Strength and Variability of Round Timber

Past research has shown that round wood timbers demonstrate higher strength and reduced variability than currently allowed by visual grading techniques. SDRT is also stronger in bending than an equivalent square section area of milled timber. This increase is due to the section geometry, wood fiber continuity, and preservation of grain orientation (Wolfe, 2000a). When round timber strength data (Wood et al. 1960) is compared to dimensional lumber strength data (Green and Evans1989) it has been shown that the Coefficient Of Variability (COV) for round timbers is about one-half to two-thirds that of conventional lumber. Wood fibers in lumber are cut and discontinuous, creating stress concentrations and fracture initiation, while wood fibers in round timber flow continuously around knots on the surface. This lowers variability, which should lead to higher design values for round timbers.

Currently the decreased variability and increased bending strength are not accounted for in design values for round timbers. This requires over-engineering structures, which equates to material waste and a higher price making round timber structural systems less price competitive.

1.3.5 Need for Machine Grading (MG) Methods to assign Design Values

A background of how design values for dimensional lumber and round timber have been and are currently assigned is discussed in the following sections to demonstrate the shortcomings of visual grading and demonstrate the need for MG methodology to assign design values.

Visual and MG Methods used for Dimensional Lumber

The principles and procedures used to assign design values for visually graded wood members were originally published by the FPL in 1923 (Galligan and McDonald 2000) and later incorporated into several ASTM standards (ASTM D245, ASTM D2899, ASTM D3200). For structural lumber, ASTM D245 outlines the practice to develop design values. Average strength values and variability are determined by ASTM D143 small clear prismatic specimens. ASTM D2555 publishes these small clear test mean and variability results for a wide range of species.

From the lower 5th percentile, adjustment factors related to the visual grading of strength degrading characteristics for specific grade levels, duration of loading, and seasoning are applied to arrive at a design value. In the late 1970’s, the dimensional lumber industry questioned the validity of deriving design values based on using small clear wood test values (ASTM D2555) and ASTM D245 procedures, and developed newer methods and procedures to assign design values with full size test specimens. For dimensional lumber (4 by and smaller), ASTM D1990, ASTM D2915, and ASTM D4761 were developed to establish allowable design values from tests of full size on-grade specimens. A multi-year, in-grade testing program of full-sized dimensional lumber was undertaken in the US and Canada to establish design values. When this testing was completed in the early 1990’s, published bending, compression, and tension design values were updated for the species tested within the in-grade program. The in-grade program described above required substantial economic investment. The first MG methods for milled lumber were developed by the Southern Yellow Pine industry, in part to avoid similar investments. Due to changing Yellow Pine resources and decreasing MOE’s, an additional small scale in-grade program was needed for lower grades of Southern Pine. A more advanced solution for the lower quality of Southern Pine logs, and a less expensive one, was the broader implementation of machine grading (MG), which helped increase yields while giving a reliable design value.

Visual Methods currently used to assign Design Values for Round Timber

Visually graded round timber design values are currently assigned based on ASTM D2899 or ASTM 3200 procedures for poles and piles. Both procedures are similar to the ASTM D245 philosophy for dimensional lumber, and grounded on small clear wood properties as a starting point. ASTM D2555 small clear mean strengths and standard derivation are used to determine the lower 5th percentile. From the 5th percentile, adjustment factors are applied to calculate the acceptable bending design value including: duration of load and factor of safety, height and variability, diameter in excess of 13.5", form and size, and grade characteristics. ASTM D2899 specifically states that no increase in design values for drying will be given for above ground or partially seasoned piles.

For round pole and pile calculations (ASTM D2899, ASTM D3200), no increase in strength is applied to account for drying below the fiber saturation point. It was assumed that any increase in drying would be offset by the effects of splitting and checking of the round wood member. Larson and others (2004a, 2004b) showed that for matched green and air-dried ponderosa pine specimens, the flexural and compression strengths increased significantly. They showed the increase is similar to those ASTM D2555 dry-green ratios for ponderosa pine. Assuming a similar relationship to the ASTM D2555 dry-green ratios for air-dried red pine, the potential increase in red pine design values would be significant. For bending, the increase could be 1.88; for MOE, the increase could be 1.27; and for compression strength, the increase could be 2.22 over the current published design values.

In addition to dry-green ratios potentially improving design values, the continuous fibers - uncut growth rings - of round timber need to be considered in an optimized grading system. Uncut fibers reduce many factors that diminish the structural capacity of conventional milled timber. However, many of these benefits are not currently reflected in pole grading, which relies on a combination of visual grading and ASTM procedures to assign design values for round timber for construction. These ASTM procedures were developed for the use of round poles and piles in an exterior environment, or for log buildings, and not for spanning applications in enclosed building structures. A MG system for round timber intended for spannining in enclosed building structures is needed and should reduce design values and expedite the timber selection process.

1.3.6 Using Machine Grading to Measure Structural Capacity of Round Timber

Visual grading methods are not optimal for assigning design values to dimensional lumber, so they are most likely also not optimal for round timber. Machine Grading (MG), which is the alternative, is considered state of the art, and better able to assign reliable design values to a highly variable natural resource stream like SDRT. Machine grading has the ability to increase production yields, assigning improved, optimal, and reliable design values to each member with a minimum research investment. For this reason, the FPL now recommends MG techniques when helping other countries establish new methods to assign allowable design values for their lumber resources, or to assign design values for unclassified wood species. The heart of MG is the ability to non-destructively measure one or more characteristics from the source material, and reliably relate it to the mechanical properties of interest. Typically, the MOE is used, but other characteristics like specific gravity can also be used. The ability to rapidly measure a characteristic of importance for each member and relate it to structural capacity gives the manufacturer the ability to assign a more reliable design value to products and increase production yields. To date, WT's round timbers have been engineered with methods established to assign design values to poles and piles assumed to be wet or unseasoned, and based on small-scale specimens and adjustment factors. A more efficient approach utilizing MG methods has not yet been established for round timbers.

A MG based metholdogy for round timbers is essential to helping round timber structural systems gain wider market acceptance.

1.3.7 Summary of Problem

In the US, and many regions around the world, under-harvesting of SDRT results in poorly managed and unhealthy forests. If higher value added products could be made from SDRT, demand for forest cullings would increase, having a positive impact on forest management. Additionally, virtually all structural materials in the construction industry have a much higher amount of embodied energy when compared to SDRT. WT has a line of products using SDRT but struggles to gain market acceptance. This is at least partly because approval is costly as well as time consuming, which makes it necessary to overdesign structures in order to get building approval. This is necessary because a generally accepted method of grading round timbers for spanning does not exists, and methods which can be used are outdated and do not take into consideration the increased strength and reduced variability of round timber over milled lumber. An efficient MG method for round timber, which takes into account its increased strength and smaller COV, would make SDRT construction members more affordable thereby help structural products which utilize SDRT to gain more market acceptance.

1.4 Focus and Goals of this Research

As discussed above, the assignment of design values to round timber structural members used in indoor applications is inefficient. Currently, design values for round timbers are based on ASTM D2899, which does not increase values for the benefits of drying, or the reduced variability in beding strength, which has been observed in round wood members. Studies have shown that both air drying and continuous fibers have significant benefit to the design value of round wood, but a broad study to investigate this would be cost prohibitive if it a large scale destructive testing were required. A better approach would be to develop MG procedures that would incorporate this assessment within the process.

The goal of this research is to develop basic relationships between stiffness and flexural strength in the wet and dried condition for red pine. The wet relationships will be used to define sorting procedures for use as a structural spanning member. The dry relationships would be used to implement an MG process that would assign reliable design values allowing for reduced product variability and increased load carrying capacity due to drying. Once these relationships are established, a secondary goal will be the preliminary development of methods for sorting material into “bins” to assign more accurate properties to members based on this NDE strength relationship making the supply chain more efficient with respect to both natural resource consumption and time.

Since destructive testing has not yet been completed due to resource constraints, the wet to dry relationships have not yet been assessed. Therefore the sections materials and methods, results and discussion focus only on the phases of the research project that have been completed up to the end of my involvement in the project. The planned methodology and anticipated results of the destructive testing and their correlation to NDE techniques will seperatley and a discussion of outlook and further research is at the end.

2 Materials and Methods

Three non-destructive evaluation (NDE) techniques were used to evaluate the Modulus of Elasticity on a set of 102, Red Pine stems (Pinus resinosa). The NDE techniques included, Transverse Vibration testing, Stress Wave testing, and Mechanical Proof Loading. Timber selection, timber processing and the methodology used for each of the NDE techniques will be discussed below.

2.1 Timber Selection

The considerations behind timber selection, harvesting and processing details are discussed in the following sections.

2.1.1 Tree Species

For this research, Red Pine (Pinus resinosa) was selected because it is an overstocked resource in the Upper Midwest and there is an abundance of small-diameter Red Pine which needs thinning and also meets the specifications for initial scaling laid out by WT. During prior research the FPL and WT had documented numerous stands with very straight stems, few lower branches, average tapers of half-inch per 10 feet, 20+ rings per perimeter inch, and a low percentage of juvenile wood on usable stems.

Red Pine (Pinus resinosa) is native to North America and is a major commercial wood around the Great Lakes and the St. Lawrence River in a band which is approximately 1,500 miles long and 500 miles wide. Wisconsin has over 650,000 acres of red pine plantation, with significant overstocking issues due to the reduction in paper and housing markets. The Lower Wisconsin River has over 7,000 acres of public and private red pine plantations with a majority of acres overstocked due to a lack of proximity to mills and low demand for the species in general.

2.1.2 Sourcing Timbers

102 Red Pine timbers where harvested form 2 different stands along the Lower Wisconsin River in USDA zone 4b. 51 specimens were taken from each location. Timbers ranged in diameter from 7.75 inches to 11.75 inches on the butt end and were cut to a length of 175 inches.

To develop a reliable relationship between NDE-determined parameters and tested strength values, several measures were taken to assure a wide distribution of the stems was selected which characterize the upper and lower limits of the strength distribution. In addition to harvesting timbers from 2 different stands, specimens were taken from different areas on the tree. Specimen within defined range of diameteres (7” to 12” on the butt end) were taken from tree tips, centers and butts. Since it is known that there is a correlation between lower MOE/strength and juvenile wood and the amount of juvinial wood varies based on how high up the tree stem you go, this helped increase the variability in bending strength. Trees were also selected from nearby the edge of stands where they are subjected to more mechanical stresses. This was to assure that the selected timbers represent the least reliable and most variable characteristics of the timber.

Once the specimens were transported to the in-field testing facility, the wet MOE of each specimen was initially measured based on a stress wave test. This was done to confirm the sample set had a representative range of bending strength for Red Pine by checking that range of wet MOEs were 1.65 standard deviations above and below the average. With the harvested sample set, this range of 0.95×10^6 psi to 1.13095×10^6 psi was easily covered.

2.2 Timber Preparation

After harvesting, timbers were transported to the Riverside Sawmill in Muscoda, WI where the infield NDE testing was conducted with support and equipment provided by the Forest Products Laboratory. On arrival, the butt ends were immediatley marked blue or red to denote which tree stand they were from. They were also number for identification for further measurements and testing.

Marked and numbered specimen at in field testing location.

After taking initial stress wave measurements to confirm there was a sufficient range of MOE's, the timbers were debarked by hand taking care that a minimum of perimeter wood was removed. They were also cut to their final length and the timber ends were sealed with hemp shield to slow the drying process and reduce checking initiated at the timber ends.

Since a main goal of the project is to investigate the correlation between NDE metrics gathered from 'green' samples with destructive tests conducted on dried timber the moisture content of the timbers needed kept above the fiber saturation point throughout the NDE process, which was spread over 2 months. This meant the timbers needed to be occasionally sprinkled with water to eliminate the effects of drying on the results. Moisture content was checked regularly to assure it did not drop below the assumed harvest-point moisture content of 30% or higher.

2.3 Basic Metrics

Several basic metrics necessary to assess the specimen for both NDE techniques and the final destructive testing were collected.

Timber Geometry

Measurements of the basic geometry were taken using a tape measurer and large caliper. Measurements included:

- Diameter at both ends (to the nearest ¼ inch)
- Circumference at both ends and center (to the nearest ½ inch)
- Length (all logs were cut to 175 inches)
- From this taper and volume for each specimen was calculated assuming the timbers are conical.

Timber Weight

The wet weight of each timber was measured using a crane scale suspended from a fork lift and attached to the timber using 2 ratchet straps. For each timber, the ratchet straps were attached 8" to each side of center slightly offset to the butt end so the timber would balance when lifted. Then the fork lift was raised until the timber was freely suspended in the air. Once the scale displayed a static measurement, the measure was recorded. Before destructive testing, the dried weight of each timber will be taken again using the same procedure. Weights were recorded to the nearest 10th of a pound and ranged from 153 lbs. to 320.2 lbs.

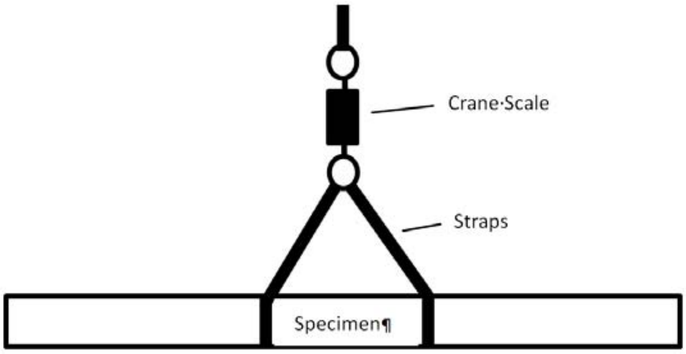


Figure 1 Weight measurement set up

Moisture Content

During the NDE testing moisture content was regularly checked to assure it stayed above the assumed harvest-point moisture content of 30%. Moisture content was measured using a standard 2-pin meter driven into the timber. When NDE testing was completed timbers were dried to average moisture content of 15% and measurements were taken to assure none are over the maximum allowable moisture content of 19% for ‘dry’ destructive testing. Moisture content will be checked and recorded again immediatley before the destructive testing to both confirm the moisture content is below 19% and for evaluation of the final results.

Number of Growth Rings

The number of growth rings was counted on the butt end of each log and recorded.

2.4 Longitudinal Stress Wave Test

A longitudinal stress wave test was conducted on each stem after they were peeled and cut to length using a Hitman HM200. The Hitman HM200 is a device which is used to determine the acoustic speed of a log. To get a proper speed reading, the length and grade of each log must be entered. Since all logs were 175 inches and above the fiber saturation point, these parameters were the same for all timbers. The grade which was selected was ‘green’ which is the setting used for round timbers which have not yet been dried.

The stress wave test was conducted by holding the Hitman HM200 firmly against the end of the timber and striking the same end with a hammer. The intensity of the strike should have no impact on the reading and this was confirmed by experimenting with harder and softer hammer strikes.

The device measures the time in which the stress wave needs to go to the end of the log and return to the device. Using the entered parameters of length and grade, it calculates the speed at which the stress wave traveled. The test was performed multiple times for each specimen until the same velocity reading was reuturned 3 times. For many specimens, the first 3 tests returned the same result, demonstrating the consistency of the method. Rarely did the test have to be conducted more than 5 times to receive 3 matching results. Once 3 matching results were obtained, that velocity was recorded for the specimen in ft/s. Velocity ranged from 10,991 ft/s to 14,633 ft/s.

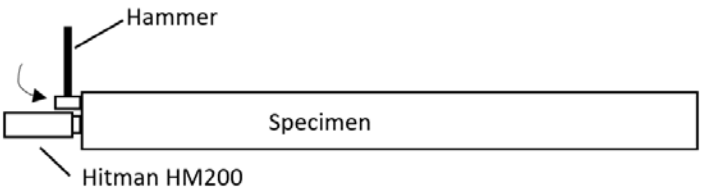


Figure 2 Experimental setup for stress-wave measurement

Once velocity for each specimen was obtained, stress wave MOE was then calculated for the wet density. The following formula from (Wolfe 2000b) was used.

$$\mathrm{MOE}_{SW} = C^2 \rho$$

Where:

MOE_{SW} = stress wave modulus of elasticity (psi)

C =stress wave velocity (ft/s)

ρ = density of timber with both mass and volume measurements above the fiber saturation point.

2.5 Transverse Vibration Test

Each specimen underwent a transverse vibration test. This was done by lifting the timbers onto two saw horses with a span of 167.75 inches using a fork lift. The specimen was struck with a hammer on the topside at the midpoint of the span. A calibrated load cell was used to measure both the first mode of vibration and specific weight. These numbers were recorded and used to calculate the MOE based on the transverse vibration test.

Figure 3 Experimental setup for transverse vibration measurement

To calculate the MOE, based on transverse vibration (MOE_{tran}) the following formula from Murphy (2011), was used:

$$MOE_{tran} = \frac{f^2 s^4}{\pi^2/4} \frac{W}{gL} \frac{64\pi^3}{c_b^4} \frac{1}{\theta}$$

where

$$\theta = \frac{(m^2 + 6mn + n^2)}{32} \frac{(1 + a + a2)}{3}$$

$$a = c_t/c_b$$

$$m = 2 + (a - 1)(1 + \frac{S}{L})$$

$$m = 2 + (a - 1)(1 - \frac{S}{L})$$

b = horizontal width of specimen
c_b = butt circumference of specimen
c_t = tip circumference of specimen
f = fundamental frequency of vibration
g = gravitational (acceleration) constant (386.089 in/s^2)
h = vertical height of specimen
L = length of specimen
S = support span (<L)
W = total weight of specimen


Figure 4 Experimental setup for mechanical loading measurement

2.6 Mechanical Proof Loading

Mechanical proof loading was conducted with a similar setup to the transverse vibration test. Each specimen was suspended between two saw horses with a span of 167.75 inches and 2 loads were applied using ratchet straps placed 6 inches from either side of the midpoint of the span. A Lineal Variable Differential Transformer (LVDT) was used to measure mid-span deformation. Each single point load was 100 lbs and they were applied one at a time. After the first load was applied the deformation reading from the LVDT was recorded. Then after the second load was applied, the deformation reading from the LVDT was recorded again. From this the zero to full load deformation could be calculated making it possible to calculate the deformation as well as the MOE for three different loads:

- Zero to half load (first 100 lbs.)
- Half load to full load (second 100 lbs.)
- Zero to full load (entire 200 lbs.)

Since the loads were applied slightly off center and deformation was measured in the middle, two different MOEs needed to be calculated for the zero to half-load deformation and half to full load deformation. These measurements and the calculated MOEs were only used to compare against the full load MOE measurements. Differences between the 5 obtained MOE measurements obtained only showed minor variations which was expected.

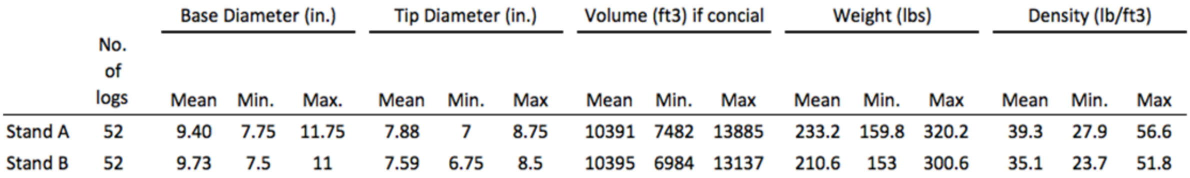
Therefore, the calculated MOE for the full load was the only measurement used for further analysis in the following section.

3 Results and Discussion

3.1 Physical Characteristics

The physical characteristics of the logs at the time of testing are summarized in Table 1. The diameter of the logs tested was on the high end of the range of 4.3 to 11 inches, which is a typical diameter range for small-diameter timber according to (Wolfe 2000) but is consistent with the diameters needed for WT’s round timber structural systems.

Table 1 Physical characteristics of green logs after harvest



	No. of logs	Base Diameter (in.)			Tip Diameter (in.)			Volume (ft3) if concial			Weight (lbs)			Density (lb/ft3)		
		Mean	Min.	Max.	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max	Mean	Min.	Max
Stand A	52	9.40	7.75	11.75	7.88	7	8.75	10391	7482	13885	233.2	159.8	320.2	39.3	27.9	56.6
Stand B	52	9.73	7.5	11	7.59	6.75	8.5	10395	6984	13137	210.6	153	300.6	35.1	23.7	51.8

3.2 Flexural Stiffeness (MOE)

The MOE results of each of NDE method are summarized in table 2. Transverse Vibration and Mechanical Loading yielded MOE results with very similar ranges, means and standard deviations. For transverse vibration the MOE ranged from $0.46x10^6$ psi to $1.82x10^6$psi with an average of $0.94x10^6$ psi. For Mechanical Loading the MOE ranged from $0.49x10^6$psi to $1.76x10^6$psi with an average of $0.95x10^6$psi. MOE results from Stress Wave testing resulted in higher MOEs with a range from $0.86x10^6$psi to $1.90x10^6$ psi. The higher range of MOE obtained from Stress Wave testing may partially be because stress wave testing was conducted several weeks before Transverse Vibration and Mechanical Loading testing was done. Despite sprinkling the logs with water regularly to prevent drying, it is likely that the moisture content during the stress wave testing was higher on average and it is certain that the moisture gradiant of the logs was different. Despite the higher MOE range, the coefficient of variablility (COV) for stress wave MOE was asignificantly lower at 16.5% than transverse vibration and mechanical loading MOE which were both over 26%. This may be due to the higher MOE range which makes for a bigger denominator in the COV equation.

Table 2 MOE derived from various NDE methods

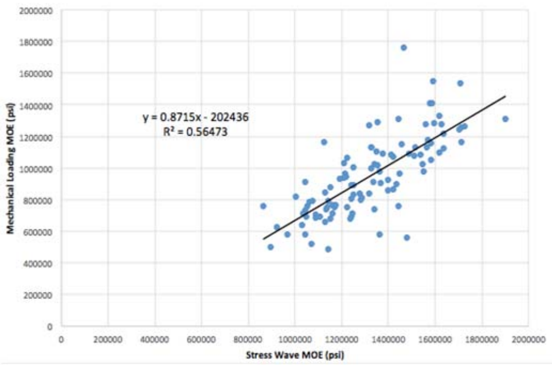
	MOE (psi)		
	Stress Wave	Transverse Vibration	Mechanical Loading
Mean	1322880	937788	950445
Max	1901194	1828336	1760662
Min	863887	463857	487220
Std. Dev.	233555	263496	277744
COV(%)	16.5%	26.2%	26.6%

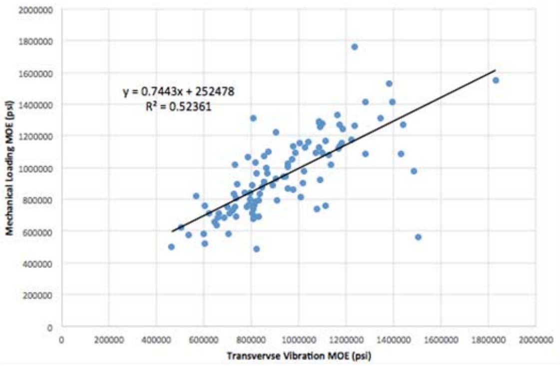
3.3 Relationship between MOE’s

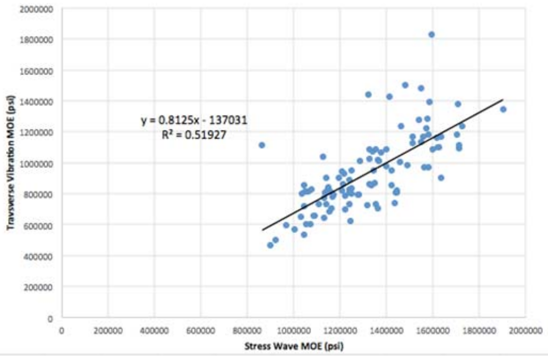
Since stiffness is the measure used most frequently to predict the strength of wood materials (Xiping, 2002), the relationship between the MOE results for each of the NDE techniques is the focus of this analysis. The realationships between the various MOE measurements were assessed by conducting a linear regression of all three MOE pairs. The pairs included Mechanical Loading MOE to Stress Wave MOE, Mechanical Loading MOE to Transverse Vibration MOE, and Transverse Vibration MOE to Stress Wave MOE. The results are summarized in table 3 and a scatter chart for each pair is below. Despite having stress wave testing supplying a significantly higher range of MOE, the strongest correlation was between stress wave testing MOE and mechanical loading MOE with an r of .7515 and an r^2 value of .5647. The relationships between the other methods were similar although slighthly lower. The r^2 values between all 3 MOE pairs were over 0.5 so the data correlation between them is significant but not particularly strong.

Table 3 Correlation of MOE values.

	Correlation of MOE obtained from NDE methods		
	Stress Wave to Transverse Vibration	Transverse Vibration to Mechanical Loading	Stress Wave to Mechanical Loading
r	0.7198	0.7225	0.7515
r^2	0.5193	0.5236	0.5647







Since destructive testing has not been completed, no MOR data exists for the sample set so at this time it is impossible create a predictive model for MOR based on the NDE data.

The next steps which will be required to develop a predictive model are discussed below.

4 Additional Testing

4.1 Photogrammetric Analyses of Timbers

Immediately before desctructive testing occurs, the cross section geometry will be measured using a close range photogrammetic technique developed in a prior research project by the Forest Products Lab. Although this is not a focus of the project, or one of the main research goals, the photogrammetic technique allows an accurate 3D model of the trees geometry to be captured. Since traditional techniques only allow for a rough estimation of a timber’s geometry by taking some physical measurements and making assumptions (i.e. the timber is perfectly connical and has a consistent taper). With an accurate 3D model, it may be possible to develop a computer based model which can more accurately predict bending strength and failure points. A computer model will likley not be developed for some time, but the photogrammetric data will be captured before destructive testing so that this can be done at a later date.

4.2 Transverse Destructive Bending Tests

In order to achieve the ultimate goal of this project which is to establish relationships between both wet MOE values and the bending strength of a dried round wood member, destructive testing still needs to completed. Due to resource shortages, this testing has been delayed until the end of January 2017.

As mentioned above, the timbers have already been dried and the moisture content will be checked again to assure moisture content is below 19% and near the desired average moisture content of 15%.

Flexural bending tests will be conducted on the dried specimens to determine both the flexural MOE and the bending strength (Modulus of Rupture (MOR)). A diagram demonstrating the layout of the test apparatus and setup is shown below. A three point flexural test will be conducted according to ASTM D198. The test will be conducted at the Engineering Mechanics Laboratory (EML) of the Forest Products Laboratory (FPL) in Madison WI.

Mid-span deformation will be measured using a yoke that is attached to the neutral axis above the end supports to aid in MOE calculations. Measurements will be recorded by computer at a minimum rate of 5 samples per second. Bending strength will be determined using the actual diameter near the failure location. Notes on the observed cause of failure will be recorded for each specimen.

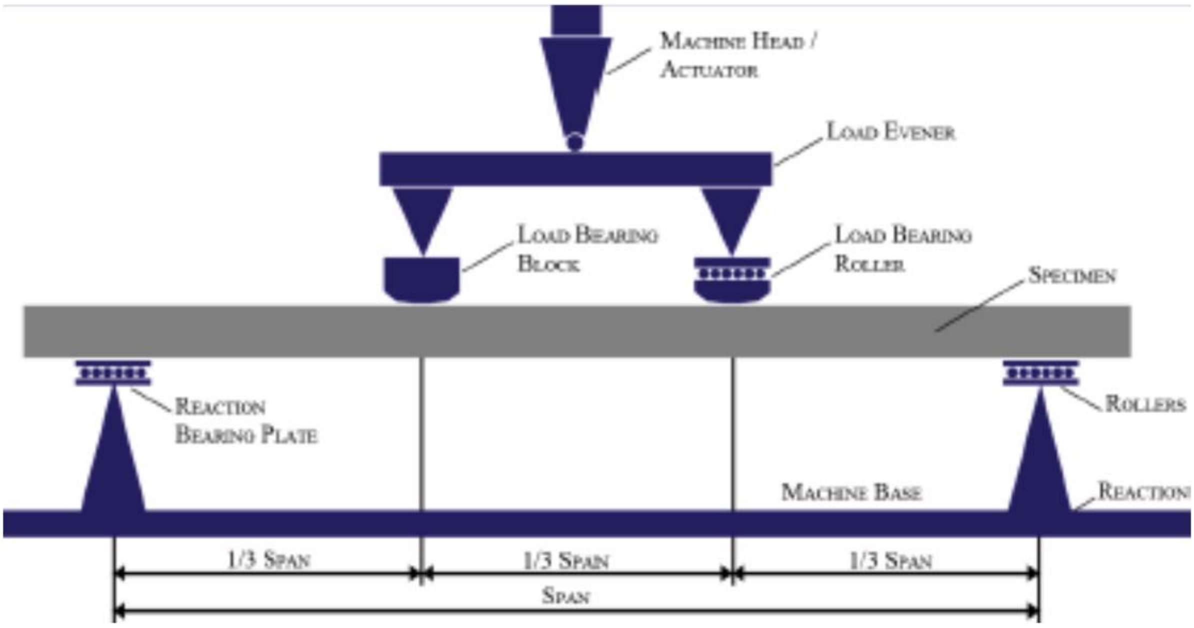


Figure 5 Flexure method testing apparatus diagram based on ASTM D198 (2009) procedures.

The wet MOE – strength relationship will be defined for all the NDE techniques (longitudinal stress wave, transverse vibration and mechanical proof loading) to determine the best method to use for selective harvesting for maximum strength capacity. Seasoned MOE strength relationships will be determined for all NDE techniques and physical testing MOE. These relationships will be the basis of the MG systems developed for Red Pine round wood and can serve as a basis for determining wet-dry relationships for other species.

To be consistent with historical dimensioned lumber techniques, the MOE obtained from through mechanical testing will be determined using linear regression of the mid-span displacement data between 20 and 40 percent of the maximum load.

4.3 Confirmation of Moisture Content

In order to get a more accurate measure of moisture content, discs will be cut from each specimen after the destructive testing. The moisture content of the discs will be measured and then used to determine the specific gravity which will be the assumed specific gravity of each timber.

4.4 Cost Benefit Analysis

Once all testing is complete and a predictive model is developed, a cost benefit anaylsis will be conducted for the selection and grading procedure which is determined to be most suitable. In order to determine costs, the equipment and time necessary to complete the selection and grading procedure will be considered and compared to the benefits which will likely be reduced design values and more efficient harvesting and sorting procedures.

5 Anticipated Results of Further Testing

The anticipated results after completion of destructive testing are discussed in section 5.1 and 5.2. First the methodolgy used to develop a predictive model for bending strength is discussed and then the likelyhood of observing a reduced coefficient of variation (COV) than what is currently assumed and the potential impact this would have on design values is discussed.

5.1 Developing a preditive model based for dry bending strength based on wet MOE

Based on work done with sawn lumber, it should be possible to develop a strong correlation between NDE measurements and the actual bending strength of the specimens. Given the correlation between various MOE measurements obtained by the NDE methods themselves, it should be possible to create a preditive model of actual bending strength based on one more more of the NDE techniques.

It will likely be the case that multiple models which can predict the actual bending strength (MOR) with one or more of the NDE MOEs along with other metrics that can be taken from ‘green’ timbers in the field (i.e. diameter, density) will be created.

If good models can be established with all MOEs, then supply chain considerations will be taken into account. Price, time, and logistical considerations for each NDE method should be taken into account as they are important in determining the best-suited NDE technique. With respect to the supply chain, longitudinal stress wave testing would be the ideal method since it is the quickest to perform and it is possible to do on standing trees or timbers, which have just been felled. This would allow timbers to be sorted into categories based on their mechanical properties in before they even leave the forest making it possible to ship them to different production facilities depending on the intended use.

Since destructive testing and the mechanical loading already conducted both involve applying a static force to the specimen and stress wave testing already demonstrated the best correlation to mechanical loading, there is a high likelyhood that stress wave testing will also correlate most closely to the destructive testing.

5.2 Reduced Coefficient of Variation

In addition to developing a predictive model for MOR based on NDE techqniques, it is expected that MOR values obtained from destructive testing will demonstrate a significantly lower variability than what is seen with sawn timber. The reasons for this were discussed in the introduction under section 1.3.4, but if a lower COV for round timber can be established, it could have a significant impact on lowering design values for spanning building members which utilize round timber.

To illustrate the effects of lower COV on design values, the distribution and lower 5th percentile limit of the in-grade data for the Red Pine 2 by 6 Select Structural is plotted in Figure 6, assuming a normal distribution. Assuming the same mean strength value but half the COV (15%), a distribution and lower 5th percentile for round wood is overlaid on the plot. For the establishment of design values, the 5th percentile is the base number from which all calculations start; therefore, by reducing variability the resulting design value will be greater. For this example, ratio of 5th percentile is 1.60. Wang and others (2001, 2003 and 2007) have shown that longitudinal stress waving of stand trees can assist manufacturing decisions by sorting the highest potential for increased value. Implementation of such a practice could further reduce the downstream variability of the candidate structural round wood member.

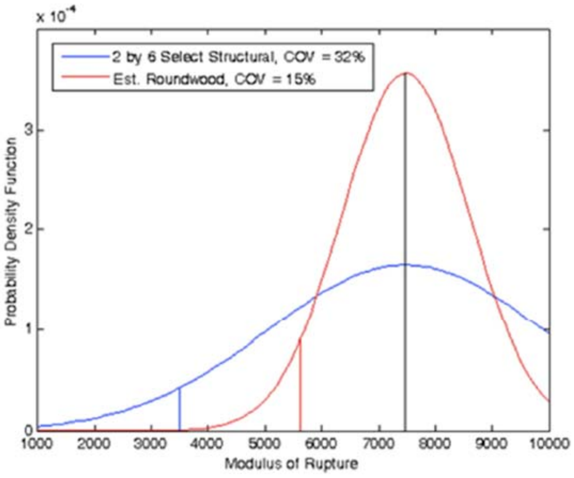


Figure 6: Estimated effects on SDRT design values if variability round timber is lowered than dimensional lumber (2x6 in this example).

This means it is highly likely that the predictive model developed after completion of the destructive testing will make it possible to greatly reduce design values for round timber structural systems. This would make it possible to use smaller members than currently required and lead to more efficient resource use and cost savings.

6 Outlook

If structural systems for SDRT can gain a significant market share, there would be 2 positive environmental impacts; 1) decreased energy consumption due to SDRT's lower embodied energy versus alternative structural materials, and 2) increased demand for forest cullings resulting in improved forest management.

Development of MG methods are crucial to bringing the strength of round timber trusses to market for structural building applications, where the benefits of drying and reduced variability are not currently realized.

After completion of this research, the ground work for a grading system based on NDE techniques which takes into account these benefits will be laid. This will help to streamline processes in the supply chain and make for more efficient use of SDRT.

Although this research focuses grading of plantation red pine, the methodologies here could be applied to other softwood species. This could benefit the construction industry and forestry branches in other regions. For example southern yellow pine in the Southeast, lodge pole pine in the West, and ponderosa pine in the Southwest.

Each species and region will have specific issues related to it, but the MG methodology established in this project could be used as a set of common core principles that can help guide the development of them all.

6.1 Economic Impact

If a successful predictive model for dry bending strength of round timber based on wet MOE can be developed and demonstrates allows for lower design values there could be several long term positive economic and environmental impacts.

First, reduced supply-chain waste and production costs will lead to price competitiveness and increased product quality. This would make it easier for round timber structural systems to gain wider market acceptance and may lead to the creation of a new category of value-added products based on forest thinnings. The increase return on investment from forest lands would also result in better forestry practices as well as additional forestry and manufacturing jobs. Since reduced transport, also helps decrease the embodied energy in a product these manufacturing could be located near overstocked forests in rural locations where jobs are often in short supply.

Additionally the increased use of round timber in non-residential products would help diversify the use forest prodcuts so they are less dependent on housing. This is important because housing tends to be cyclical. Any additional market for forest products help to reduce to tendency of forests to become overstocked when the residential housing market is in a slump.

6.2 Social and Environmental Impact

In addition to the positive social impact in the way of stable manufacturing and forestry jobs in rural areas, better forestry practices would help reduce the risk of wild fires and disease pressures from poorly managed forest stnads. In general more demand for forest thinnings would help to contribute to forest health, diversity and the ability of forests to sequestered forests.

Additionally carbon sequestration would be increased through more timber structures, and the carbon footprint of building projects could be reduced due to the reduction in embodied energy.

6.3 Further Research

In order for round timber structural systems to gain a truly broad market acceptance more accurate and more advantageous design values will help but further research will be needed to before standardized load tables will be accepted. Additionally other hurdles will need to be overcome. Software and IT supported processes need to be developed to make production more replicable and cost effecitve. Research also needs to be conducted on other elements of WT round timber structural systems so that complete structural solutions can be offered to the market.

6.4 Conclusion

Widespread use of round timber structural systems could potentially have a significant positive impact on the enviornment, forestry management and the economy. Developing an efficient way to grade round timbers which takes into account their reduced variabliltiy over sawn timber is one of the keys to helping gain wider market acceptance. This research project makes a significant step towards establishing a more favorable grading system for round timbers.

7 Data

7.1 Basic Specimen Data

#	Length(in)	BaseØ(in)	BaseC (in)	TopØ (in)	TopC (in)	AvgØ (in)	MidC(in)	Weight(lbs)	Stand
1	175	11,25	37	8,5	28	9,875	30	286,4	A
2	175	9,5	32	7,75	26	8,625	27	229,6	A
3	175	10,75	35	8,5	28	9,625	29	218,6	A
4	175	11,25	36	8,5	30	9,875	30	286,1	A
5	175	10	34	8,5	28	9,25	28,5	211,8	A
6	175	8	26	7	23	7,5	23,5	180	A
7	175	8,5	28	7,25	24	7,875	26	203	A
8	175	8	26	7	23	7,5	25	159,8	A
9	175	10	32	7,5	24	8,75	26	213	A
10	175	10,5	35,5	8,25	26,5	9,375	30	250,6	A
11	175	8,5	29	7,75	25	8,125	27	222,4	A
12	175	10,75	37	8,25	28	9,5	29	263,4	A
13	175	8	26	7,25	24	7,625	27	182,6	A
14	175	8,75	29	7,5	27	8,125	28	197,2	A
15	175	10,25	35	8	28	9,125	29	268,8	A
16	175	10	31,5	7	24	8,5	24	300,6	B
17	175	9,25	29	7,25	25	8,25	26	250,6	B
18	175	9,5	33	7,75	26	8,625	30	231,6	A
19	175	11,25	36	8,25	27	9,75	29,5	282,2	A
20	175	8,25	29	7,75	26,5	8	28	242	A
21	175	10,25	34	8,75	30	9,5	32	284	A
22	175	8	26,5	7,5	25,5	7,75	26,5	220,2	A
23	175	8,75	28,5	8	25,5	8,375	27	226,4	A
24	175	11,25	37	8,75	28	10	31	320,2	A
25	175	10,75	34,5	8,5	27	9,625	28	247,2	A
26	175	11	36	7,75	26	9,375	27,5	212,4	A
27	175	7,75	25	7	22	7,375	23	245	A
28	175	10	32,5	8,5	27,5	9,25	28,5	292,8	A
29	175	9,5	31,5	7,5	25	8,5	26	180,4	B
30	175	8,75	27	7,25	23,5	8	25	206,2	A
31	175	9,75	30	8,5	28	9,125	28	237,2	A
32	175	8	26,5	7	23	7,5	24,5	185,4	A
33	175	8,5	27,5	7,75	25	8,125	26	225,4	A
34	175	8,5	29	8	25,5	8,25	27	225,8	A
35	175	9,5	32	8,25	27	8,875	28	233,8	A
36	175	8,25	27	7,25	24	7,75	26	231	A
37	175	11,75	35	8,25	26,5	10	29	306,2	A
38	175	8,5	28	7,75	25	8,125	28	226	A
39	175	8,5	27	7,5	24,5	8	26	224,4	A

40	175	8,5	28	8	24	8,25	26	189,2	A
41	175	11	36	8,25	27	9,625	29,5	274,2	A
42	175	8,25	28	7,75	25	8	25	210,2	A
43	175	9	28,5	8,25	27	8,625	28	229,6	A
44	175	8,5	28	7,5	25	8	27	255,5	A
45	175	8,75	29	8,25	26	8,5	27	229,2	A
46	175	8,25	28	7,5	24	7,875	26	230,6	A
47	175	9	29,5	7,25	23,5	8,125	27	196,2	A
48	175	8,75	29	7,5	25	8,125	27,5	216,8	A
49	175	8	27	7	23	7,5	24	167	A
50	175	9,5	30	8,25	26	8,875	27,5	210,8	A
51	175	11,25	36	8,75	30	10	29,5	288	A
52	175	11	35,5	8	26	9,5	28,5	282,4	A
53	175	11,25	36,5	8,5	28	9,875	29	307,6	A
54	175	8,25	27	7,5	25	7,875	25	168,7	A
55	175	9,25	31	8,5	27	8,875	29,5	270	A
56	175	10,25	33	7,75	25	9	27	207,8	B
57	175	9,25	29,5	7,5	24	8,375	25	167	B
58	175	9,5	30,5	7,5	24	8,5	25	243	B
59	175	9,75	31	7,5	25	8,625	26	195	B
60	175	9,5	31	7,25	24	8,375	25	194,4	B
61	175	9,75	31	7,5	26	8,625	27,5	199,2	B
62	175	8,75	28	7	22,5	7,875	24	171,8	B
63	175	9,75	31	7,5	24	8,625	26	185,6	B
64	175	9,75	30,5	7,75	25	8,75	26	210,2	B
65	175	9,75	31	7,25	23,5	8,5	25	193,8	B
66	175	9,25	30	7,5	23	8,375	24	198,8	B
67	175	9,25	28	7	22	8,125	23,5	172,8	B
68	175	10,25	32	8	25,5	9,125	27	182,4	B
69	175	10	31	7,5	24	8,75	25	202,4	B
70	175	9,75	32	7,25	23	8,5	25	188,3	B
71	175	10	31,5	7,5	24	8,75	26	205,4	B
72	175	10	31	7,75	24,5	8,875	27,5	249,2	B
73	175	10,25	32	7,5	25	8,875	26	218,8	B
74	175	9,75	31,5	7,75	25,5	8,75	27,5	229,8	B
75	175	10,25	30,5	7,5	24,5	8,875	26	203,8	B
76	175	10	33	7,5	25	8,75	26,5	224,6	B
77	175	10	31	8	25	9	28	220	B
78	175	10,25	32,5	7,5	26	8,875	27	186,2	B
79	175	9,75	30	8	25	8,875	26	201,8	B
80	175	10	32	8	26	9	27,5	153	B
81	175	9,5	30	7,5	24	8,5	25	239,8	B
82	175	11	30	8,5	23	9,75	25,5	201	B
83	175	8,5	30	7,25	24,5	7,875	25,5	183,4	B
84	175	10,25	32	7,5	25,5	8,875	29	212,2	B

85	175	9,25	28,5	7	23	8,125	24,5	204,4	B
86	175	9,75	31	7,25	24	8,5	25,5	182,6	B
87	175	9	27	7,5	23,5	8,25	24	224	B
88	175	10	32	8	26	9	29	216	B
89	175	10,25	32	7,75	25	9	26,5	216	B
90	175	9,25	29,5	7,5	25	8,375	25	249	B
91	175	10,25	31,5	7,5	24,5	8,875	26	199,6	B
92	175	10	30	7,5	24,5	8,75	25	166,8	B
93	175	9,75	32,5	7,75	25,5	8,75	26,5	218,6	B
94	175	7,75	26	7	23	7,375	25,5	186,6	A
95	175	10,75	36,5	8,25	28	9,5	30,5	201,2	A
96	175	11,5	38	8,5	28	10	30,5	298,4	A
97	175	9,25	28,5	7,75	23,5	8,5	25	207,6	B
98	175	9,25	30	7,75	24	8,5	25	216	B
99	175	7,5	24	6,75	21	7,125	22,5	156,4	A
100	175	10	27,5	8,25	24	9,125	25,5	300,6	A
101	175	10,5	35,5	8,25	26,5	9,375	30	297,8	A
102	175	9	36,5	8	29	8,5	30	180,4	A

7.2 Stress Wave Data

#	Velocity (ft/s)	Volume (in3)	Wet Weight (lbs)	MOEraw (PSI)
1	13123	13489,52525	0,587682061	1363918,668
2	12566	10259,59859	0,619451916	1318200,564
3	12795	12790,85317	0,473060547	1043703,386
4	12434	13489,52525	0,587066472	1223175,536
5	12238	11785,7962	0,497431306	1004000,188
6	12992	7742,661063	0,643499691	1463794,626
7	13255	8541,552496	0,657847622	1557630,90
8	14501	7742,661063	0,571284726	1618930,852
9	12434	10594,61758	0,556493895	1159476,40
10	12106	12137,99565	0,571478867	1128707,20
11	13681	9079,873605	0,67798653	1710159,17
12	12566	12475,87805	0,584400711	1243611,21
13	13812	7997,504566	0,631993137	1624820,10
14	13255	9091,327246	0,600406943	1421624,672
15	12861	11502,3186	0,646859495	1441913,526
16	11909	10033,38919	0,829291862	1585031,056
17	12566	9400,575543	0,737891842	1570242,043
18	13058	10259,59859	0,624847838	1435844,411
19	10991	13168,82331	0,593165829	965673,5191
20	12631	8799,25941	0,761264066	1636781,029
21	11909	12430,06349	0,632427985	1208763,817
22	13123	8258,074891	0,738081948	1712973,415

23	13255	9646,828816	0,64961783	1538144,661
24	12172	13815,954	0,641514585	1280885,189
25	12730	12790,85317	0,534952275	1168292,606
26	13812	12200,99068	0,481865133	1238849,142
27	11417	7482,090738	0,906377674	1592183,00
28	11614	11785,7962	0,687667075	1250033,513
29	13615	9976,120984	0,500542446	1250420,212
30	12730	8822,166691	0,646963065	1412915,133
31	13451	11462,23086	0,572811356	1396691,682
32	13451	7742,661063	0,662804682	1616123,311
33	12929	9079,873605	0,687132032	1547924,761
34	12861	9357,624391	0,667919948	1488859,351
35	13386	10843,73426	0,596804002	1441163,153
36	12303	8266,665121	0,773477564	1577791,277
37	12500	13884,67585	0,610429519	1285391,237
38	13550	9079,873605	0,688961132	1704720,149
39	13123	8807,849641	0,705210949	1636684,938
40	13255	9357,624391	0,559656573	1325137,228
41	11680	12819,48727	0,592056128	1088499,787
42	13386	8799,25941	0,661230193	1596739,612
43	13747	10230,96449	0,621185618	1582038,469
44	13255	8807,849641	0,802947404	1901193,602
45	13255	9933,169832	0,638694003	1512279,567
46	13085	8530,098855	0,748292383	1726627,129
47	11417	9108,507707	0,596235539	1047373,648
48	13255	9091,327246	0,660082278	1562922,053
49	13451	7742,661063	0,597024713	1455731,354
50	12500	10843,73426	0,538093599	1133072,33
51	12172	13815,954	0,5770025	1152076,622
52	11220	12507,37556	0,624977795	1060303,227
53	11680	13489,52525	0,631183666	1160436,069
54	14633	8530,098855	0,547428122	1579696,41
55	12369	10832,28062	0,689937813	1422521,728
56	12861	11204,52394	0,513355501	1144319,974
57	13615	9675,462918	0,47776112	1193509,492
58	12238	9976,120984	0,674234004	1360853,365
59	13747	10282,50587	0,524930408	1336895,244
60	13320	9698,370199	0,554834667	1326636,128
61	12500	10282,50587	0,536236601	1129162,019
62	13550	8558,732957	0,55562243	1374795,625
63	13451	10282,50587	0,49962607	1218243,264
64	12927	10568,84689	0,550517579	1239785,266
65	12927	10001,89168	0,536336942	1207849,966
66	11680	9675,462918	0,568735992	1045625,535
67	12631	9131,414988	0,523807538	1126229,751

68	13189	11502,3186	0,438940372	1028985,004
69	13189	10594,61758	0,528799832	1239637,848
70	12369	10001,89168	0,521115822	1074442,602
71	12730	10594,61758	0,536637775	1171973,601
72	12795	10883,822	0,633771482	1398276,489
73	12927	10912,45611	0,55499733	1249873,825
74	12861	10568,84689	0,601850331	1341583,667
75	12795	10912,45611	0,516949067	1140533,689
76	12434	10594,61758	0,586800605	1222621,59
77	13550	11178,75325	0,544747689	1347887,882
78	12861	10912,45611	0,472305772	1052816,084
79	12230	10860,91472	0,514305115	1036701,054
80	13255	11178,75325	0,378847257	897022,6158
81	12992	9976,120984	0,665355203	1513510,238
82	12303	13137,3258	0,423501715	863887,1277
83	12992	8541,552496	0,5943313	1351949,31
84	12238	10912,45611	0,538256094	1086399,695
85	12795	9131,414988	0,619596416	1367002,344
86	12992	10001,89168	0,505341206	1149519,964
87	13189	9380,531672	0,66097746	1549494,962
88	12566	11178,75325	0,534843186	1138152,246
89	13123	11204,52394	0,533613033	1238432,862
90	11745	9675,462918	0,712350412	1324279,037
91	12730	10912,45611	0,506295553	1105708,637
92	13320	10594,61758	0,435789585	1041993,665
93	12861	10568,84689	0,57251733	1276197,518
94	13550	7482,090738	0,690326833	1708099,348
95	12369	12475,87805	0,446398721	920390,0228
96	11549	13847,45152	0,596478853	1072169,864
97	13123	9956,077113	0,577171906	1339526,232
98	12927	9956,077113	0,600525682	1352405,302
99	12566	6983,857371	0,619879784	1319111,073
100	12303	11479,41132	0,724828806	1478554,287
101	12566	12137,99565	0,679115748	1445165,863
102	13386	9941,760063	0,502272432	1212888,183

7.3 Transverse Vibration Data

#	f	a	m	n	q	MOEtran (PSI)
1	17,0311	0,75676	1,52359	1,98992	0,59381	703582,64
2	15,4059	0,81250	1,63277	1,99223	0,67359	727214,60
3	15,9473	0,80000	1,60829	1,99171	0,65506	533069,10
4	17,4943	0,83333	1,67357	1,99310	0,70532	696669,96
5	16,2032	0,82353	1,65437	1,99269	0,69026	568217,04

6	*16,1965*	*0,88462*	*1,77401*	*1,99522*	*0,78807*	*1235865,63*
7	*16,7015*	*0,85714*	*1,72020*	*1,99408*	*0,74291*	*1168838,67*
8	*16,2070*	*0,88462*	*1,77401*	*1,99522*	*0,78807*	*1098597,07*
9	*15,7539*	*0,75000*	*1,51036*	*1,98964*	*0,58464*	*812802,34*
10	*15,8444*	*0,74648*	*1,50346*	*1,98950*	*0,57989*	*643851,13*
11	*16,6236*	*0,86207*	*1,72985*	*1,99429*	*0,75086*	*1090804,58*
12	*16,6945*	*0,75676*	*1,52359*	*1,98992*	*0,59381*	*621755,03*
13	*15,7928*	*0,92308*	*1,84934*	*1,99681*	*0,85463*	*1099160,94*
14	*16,8041*	*0,93103*	*1,86493*	*1,99714*	*0,86890*	*854062,67*
15	*17,7016*	*0,80000*	*1,60829*	*1,99171*	*0,65506*	*807631,66*
16	*17,0503*	*0,76190*	*1,53367*	*1,99014*	*0,60088*	*1392319,77*
17	*16,5695*	*0,86207*	*1,72985*	*1,99429*	*0,75086*	*1221129,95*
18	*16,0097*	*0,78788*	*1,58455*	*1,99121*	*0,63745*	*740143,80*
19	*14,8576*	*0,75000*	*1,51036*	*1,98964*	*0,58464*	*597961,77*
20	*15,3357*	*0,91379*	*1,83116*	*1,99643*	*0,83820*	*904891,49*
21	*17,8940*	*0,88235*	*1,76958*	*1,99513*	*0,78428*	*817829,47*
22	*15,6431*	*0,96226*	*1,92609*	*1,99844*	*0,92659*	*1111486,79*
23	*17,8402*	*0,89474*	*1,79383*	*1,99564*	*0,80520*	*1278512,47*
24	*17,1160*	*0,75676*	*1,52359*	*1,98992*	*0,59381*	*794479,30*
25	*17,3073*	*0,78261*	*1,57422*	*1,99099*	*0,62990*	*782115,78*
26	*18,3763*	*0,72222*	*1,45595*	*1,98849*	*0,54798*	*734531,62*
27	*15,5350*	*0,88000*	*1,76497*	*1,99503*	*0,78035*	*1828335,56*
28	*16,7114*	*0,84615*	*1,69868*	*1,99363*	*0,72538*	*952379,14*
29	*17,3346*	*0,79365*	*1,59585*	*1,99145*	*0,64579*	*803603,69*
30	*17,2828*	*0,87037*	*1,74611*	*1,99463*	*0,76441*	*1429060,06*
31	*17,5581*	*0,93333*	*1,86943*	*1,99724*	*0,87306*	*974669,60*
32	*15,7922*	*0,86792*	*1,74132*	*1,99453*	*0,76040*	*1162208,91*
33	*15,9286*	*0,90909*	*1,82195*	*1,99623*	*0,82997*	*1135614,45*
34	*15,9526*	*0,87931*	*1,76362*	*1,99500*	*0,77920*	*982793,75*
35	*16,6424*	*0,84375*	*1,69397*	*1,99353*	*0,72159*	*806677,13*
36	*15,7687*	*0,88889*	*1,78238*	*1,99540*	*0,79527*	*1280996,21*
37	*17,6546*	*0,75714*	*1,52435*	*1,98994*	*0,59434*	*1008617,83*
38	*16,5616*	*0,89286*	*1,79015*	*1,99556*	*0,80200*	*1185277,88*
39	*15,5648*	*0,90741*	*1,81865*	*1,99616*	*0,82704*	*1165856,02*
40	*16,2032*	*0,85714*	*1,72020*	*1,99408*	*0,74291*	*1025345,65*
41	*15,8381*	*0,75000*	*1,51036*	*1,98964*	*0,58464*	*660226,11*
42	*16,4369*	*0,89286*	*1,79015*	*1,99556*	*0,80200*	*1085874,65*
43	*17,9764*	*0,94737*	*1,89692*	*1,99782*	*0,89874*	*1179450,98*
44	*16,5869*	*0,89286*	*1,79015*	*1,99556*	*0,80200*	*1344090,51*
45	*17,2692*	*0,89655*	*1,79739*	*1,99571*	*0,80830*	*1126954,30*
46	*16,1031*	*0,85714*	*1,72020*	*1,99408*	*0,74291*	*1234314,58*
47	*14,6994*	*0,79661*	*1,60165*	*1,99157*	*0,65010*	*811600,95*
48	*15,9079*	*0,86207*	*1,72985*	*1,99429*	*0,75086*	*973748,93*
49	*15,7771*	*0,85185*	*1,70984*	*1,99386*	*0,73443*	*1003872,64*
50	*15,7791*	*0,86667*	*1,73886*	*1,99448*	*0,75834*	*805375,92*

51	*17,2618*	*0,83333*	*1,67357*	*1,99310*	*0,70532*	*682779,91*
52	*16,5136*	*0,73239*	*1,47588*	*1,98891*	*0,56120*	*814383,35*
53	*16,2022*	*0,76712*	*1,54389*	*1,99035*	*0,60810*	*705183,45*
54	*16,7098*	*0,92593*	*1,85492*	*1,99693*	*0,85972*	*971761,82*
55	*16,2572*	*0,87097*	*1,74728*	*1,99465*	*0,76539*	*951567,93*
56	*17,1799*	*0,75758*	*1,52519*	*1,98996*	*0,59493*	*819363,36*
57	*17,1331*	*0,81356*	*1,63484*	*1,99228*	*0,67518*	*903637,60*
58	*15,6619*	*0,78689*	*1,58260*	*1,99117*	*0,63602*	*1020790,85*
59	*16,8813*	*0,80645*	*1,62092*	*1,99198*	*0,66458*	*853427,49*
60	*16,3991*	*0,77419*	*1,55774*	*1,99065*	*0,61799*	*863426,66*
61	*16,4733*	*0,83871*	*1,68410*	*1,99332*	*0,71369*	*773056,28*
62	*16,3694*	*0,80357*	*1,61528*	*1,99186*	*0,66032*	*1069096,88*
63	*17,4429*	*0,77419*	*1,55774*	*1,99065*	*0,61799*	*932619,56*
64	*16,2973*	*0,81967*	*1,64681*	*1,99253*	*0,68440*	*888528,00*
65	*16,8460*	*0,75806*	*1,52615*	*1,98998*	*0,59560*	*942449,43*
66	*13,7650*	*0,76667*	*1,54300*	*1,99033*	*0,60747*	*721566,58*
67	*15,7793*	*0,78571*	*1,58031*	*1,99112*	*0,63434*	*1040104,00*
68	*16,0950*	*0,79688*	*1,60217*	*1,99158*	*0,65049*	*652951,80*
69	*15,7503*	*0,77419*	*1,55774*	*1,99065*	*0,61799*	*829234,44*
70	*16,3153*	*0,71875*	*1,44915*	*1,98835*	*0,54352*	*828973,91*
71	*15,5482*	*0,76190*	*1,53367*	*1,99014*	*0,60088*	*791127,79*
72	*16,5641*	*0,79032*	*1,58933*	*1,99131*	*0,64097*	*1088705,93*
73	*16,3172*	*0,78125*	*1,57156*	*1,99094*	*0,62797*	*833902,89*
74	*17,0279*	*0,80952*	*1,62694*	*1,99211*	*0,66915*	*953284,73*
75	*16,4060*	*0,80328*	*1,61471*	*1,99185*	*0,65989*	*905430,13*
76	*16,1619*	*0,75758*	*1,52519*	*1,98996*	*0,59493*	*783762,20*
77	*16,0633*	*0,80645*	*1,62092*	*1,99198*	*0,66458*	*871791,16*
78	*15,8303*	*0,80000*	*1,60829*	*1,99171*	*0,65506*	*601804,91*
79	*15,5055*	*0,83333*	*1,67357*	*1,99310*	*0,70532*	*800449,21*
80	*15,0726*	*0,81250*	*1,63277*	*1,99223*	*0,67359*	*463857,23*
81	*16,5712*	*0,80000*	*1,60829*	*1,99171*	*0,65506*	*1169777,55*
82	*16,9899*	*0,76667*	*1,54300*	*1,99033*	*0,60747*	*1111438,15*
83	*15,2613*	*0,81667*	*1,64093*	*1,99240*	*0,67985*	*731132,06*
84	*14,9783*	*0,79688*	*1,60217*	*1,99158*	*0,65049*	*657877,08*
85	*15,2075*	*0,80702*	*1,62203*	*1,99201*	*0,66542*	*1014929,30*
86	*16,7064*	*0,77419*	*1,55774*	*1,99065*	*0,61799*	*841696,82*
87	*16,8990*	*0,87037*	*1,74611*	*1,99463*	*0,76441*	*1484238,33*
88	*15,9205*	*0,81250*	*1,63277*	*1,99223*	*0,67359*	*730606,80*
89	*16,1365*	*0,78125*	*1,57156*	*1,99094*	*0,62797*	*805099,07*
90	*15,9590*	*0,84746*	*1,70123*	*1,99368*	*0,72745*	*1085015,03*
91	*15,4850*	*0,77778*	*1,56476*	*1,99079*	*0,62304*	*735424,50*
92	*17,3038*	*0,81667*	*1,64093*	*1,99240*	*0,67985*	*854855,01*
93	*16,4939*	*0,78462*	*1,57815*	*1,99108*	*0,63277*	*794020,84*
94	*16,8012*	*0,88462*	*1,77401*	*1,99522*	*0,78807*	*1378632,91*
95	*16,9126*	*0,76712*	*1,54389*	*1,99035*	*0,60810*	*502593,11*

96	15,9238	0,73684	1,48459	1,98910	0,56706	603177,49
97	15,8413	0,82456	1,65639	1,99273	0,69183	1075826,83
98	16,8273	0,80000	1,60829	1,99171	0,65506	1086497,70
99	15,8101	0,87500	1,75518	1,99482	0,77204	1438583,78
100	15,2596	0,87273	1,75073	1,99473	0,76829	1501534,26
101	16,4310	0,74648	1,50346	1,98950	0,57989	822821,22
102	17,3671	0,79452	1,59755	1,99149	0,64706	865097,54

7.3.1 Proof Loading Data

				Modulus of Elasticity (psi) for:				
	Midspan Deformation Readings (in.)			Zero to Half Load		Half to Full Load		
#	0 to 1/2	1/2 to Full	0 to Full	a < L/2	a > L/2	a < L/2	a > L/2	Full Load
1	0,03072	0,04388	0,07460	714425,54	696434,26	500184,17	487588,10	581001,23
2	0,04130	0,04632	0,08762	896599,90	880118,98	799300,33	784607,93	837391,24
3	0,04175	0,04071	0,08246	575950,18	563761,82	590677,51	578177,48	577056,77
4	0,02961	0,02804	0,05765	741255,70	722588,77	782843,44	763129,20	751894,02
5	0,03651	0,03082	0,06733	759961,24	748785,52	900220,81	886982,48	818094,05
6	0,03154	0,04053	0,07207	2023882,99	1999394,36	1574852,52	1555797,08	1760661,87
7	0,04008	0,04218	0,08227	1316706,24	1297751,44	1251064,45	1233054,61	1273811,20
8	0,06106	0,05471	0,11577	1045370,68	1032721,88	1166624,59	1152508,63	1095984,26
9	0,04778	0,04432	0,09210	746667,11	727378,87	804961,00	784166,87	764712,57
10	0,03909	0,04148	0,08057	684581,91	669710,58	645023,96	631011,96	657000,03
11	0,03360	0,03935	0,07295	1368933,55	1357454,72	1168958,20	1159156,21	1255762,88
12	0,03568	0,03493	0,07060	715356,90	698327,11	730800,82	713403,38	714390,57
13	0,04509	0,04766	0,09275	1316472,22	1304711,18	1245564,65	1234437,07	1274319,44
14	0,04127	0,04499	0,08626	1127384,93	1111653,02	1034213,04	1019781,28	1071264,07
15	0,01699	0,02799	0,04497	1758021,36	1718791,41	1066847,43	1043040,91	1313091,52
16	0,02880	0,02818	0,05698	1417954,62	1372779,66	1448795,03	1402637,52	1410403,21
17	0,03741	0,03777	0,07517	1193431,63	1167246,11	1182118,58	1156181,29	1174717,76
18	0,03880	0,04292	0,08172	954228,89	936688,66	862734,80	846876,37	897849,74
19	0,03804	0,04087	0,07890	612048,51	595030,58	569620,85	553782,62	581869,55
20	0,04045	0,03915	0,07959	1204056,17	1197215,12	1244009,91	1236941,86	1220230,66
21	0,02303	0,02488	0,04792	1081710,23	1066219,99	1001327,54	986988,38	1032521,69
22	0,04619	0,04840	0,09459	1197577,48	1190554,09	1142772,12	1136070,15	1166103,64
23	0,03691	0,03777	0,07467	1103534,25	1094556,47	1078318,46	1069545,82	1086343,63
24	0,02550	0,02586	0,05136	812549,10	794166,89	801361,46	783232,35	797804,65
25	0,03149	0,03192	0,06340	763690,04	747528,69	753472,41	737527,29	750520,57
26	0,03020	0,03718	0,06737	912079,64	883533,78	740811,70	717626,11	804778,51
27	0,03988	0,04734	0,08722	1702021,46	1686301,86	1433727,82	1420486,14	1549192,00
28	0,02729	0,02746	0,05476	1016483,66	1001535,61	1010228,49	995372,43	1005895,47
29	0,04492	0,04275	0,08767	880499,11	861744,73	925065,70	905362,07	892623,74
30	0,04485	0,04623	0,09108	1111577,12	1092688,20	1078372,39	1060047,71	1085421,76
31	0,03353	0,03390	0,06743	869238,72	858433,89	859904,75	849215,94	859186,03

32	*0,04697*	*0,04832*	*0,09529*	*1358863,93*	*1342421,92*	*1321009,12*	*1305025,14*	*1331564,29*
33	*0,04582*	*0,04385*	*0,08967*	*1003822,86*	*995405,57*	*1048991,23*	*1040195,19*	*1021620,27*
34	*0,03994*	*0,03878*	*0,07871*	*1077804,37*	*1071865,93*	*1110159,35*	*1104042,64*	*1090729,51*
35	*0,04750*	*0,03788*	*0,08537*	*686314,70*	*677544,17*	*860706,58*	*849707,48*	*758801,66*
36	*0,04911*	*0,02964*	*0,07875*	*1139078,94*	*1125739,48*	*1887102,68*	*1865003,30*	*1412322,67*
37	*0,02519*	*0,02641*	*0,05160*	*845386,50*	*818675,69*	*806488,34*	*781006,56*	*812438,52*
38	*0,03494*	*0,03880*	*0,07374*	*1316395,28*	*1305356,99*	*1185437,68*	*1175497,51*	*1242258,77*
39	*0,04148*	*0,04574*	*0,08722*	*1186712,85*	*1173248,53*	*1076240,11*	*1064029,20*	*1122376,44*
40	*0,03748*	*0,03855*	*0,07603*	*1148639,90*	*1142311,17*	*1116638,88*	*1110486,47*	*1129308,55*
41	*0,03317*	*0,03465*	*0,06783*	*734513,02*	*715538,75*	*703162,89*	*684998,47*	*709215,88*
42	*0,03759*	*0,03788*	*0,07547*	*1295399,69*	*1288039,66*	*1285721,04*	*1278416,00*	*1286876,00*
43	*0,02971*	*0,03273*	*0,06244*	*1218213,90*	*1208589,80*	*1105731,32*	*1096995,85*	*1154671,31*
44	*0,03869*	*0,03602*	*0,07472*	*1272218,50*	*1257784,03*	*1366625,65*	*1351120,05*	*1310257,89*
45	*0,03292*	*0,03775*	*0,07066*	*1160243,36*	*1154038,45*	*1011777,95*	*1006367,02*	*1078046,19*
46	*0,03984*	*0,04228*	*0,08212*	*1309051,43*	*1297727,08*	*1233410,74*	*1222740,74*	*1264612,17*
47	*0,05628*	*0,07887*	*0,13515*	*837846,72*	*821502,98*	*597812,43*	*586151,00*	*690947,57*
48	*0,04257*	*0,03897*	*0,08154*	*1092905,58*	*1077654,80*	*1193953,56*	*1177292,73*	*1133234,77*
49	*0,05245*	*0,05761*	*0,11006*	*1216868,72*	*1202144,82*	*1107918,73*	*1094513,10*	*1152844,79*
50	*0,04306*	*0,04422*	*0,08727*	*757118,75*	*747443,41*	*737289,65*	*727867,71*	*742299,16*
51	*0,02881*	*0,03122*	*0,06003*	*719169,83*	*702900,13*	*663634,68*	*648621,35*	*682478,93*
52	*0,02952*	*0,03533*	*0,06484*	*877013,93*	*851991,82*	*732797,94*	*711890,46*	*787055,85*
53	*0,03267*	*0,02819*	*0,06086*	*671806,23*	*654888,23*	*778511,74*	*758906,59*	*712152,25*
54	*0,04831*	*0,05025*	*0,09855*	*1079521,65*	*1070182,91*	*1037861,93*	*1028883,59*	*1053704,46*
55	*0,03837*	*0,03578*	*0,07415*	*840891,76*	*834435,32*	*901806,53*	*894882,38*	*866955,16*
56	*0,09413*	*0,03479*	*0,12892*	*337887,29*	*329399,67*	*914271,27*	*891305,05*	*487219,90*
57	*0,04362*	*0,04513*	*0,08874*	*956234,45*	*938135,33*	*924174,91*	*906682,60*	*931036,11*
58	*0,03825*	*0,04183*	*0,08008*	*1033885,58*	*1011864,12*	*945522,46*	*925383,11*	*977212,50*
59	*0,04249*	*0,03884*	*0,08133*	*883595,60*	*862742,48*	*966532,21*	*943721,76*	*912311,03*
60	*0,04233*	*0,04164*	*0,08397*	*999643,51*	*975351,96*	*1016281,03*	*991585,18*	*995659,46*
61	*0,04172*	*0,04618*	*0,08790*	*899838,87*	*878602,41*	*812992,14*	*793805,29*	*844133,93*
62	*0,04851*	*0,04857*	*0,09707*	*1103232,02*	*1081031,95*	*1101869,08*	*1079696,43*	*1091456,95*
63	*0,03837*	*0,04022*	*0,07860*	*978421,17*	*955330,14*	*933395,74*	*911367,33*	*944104,65*
64	*0,03797*	*0,04007*	*0,07804*	*926113,01*	*906947,55*	*877575,80*	*859414,80*	*891866,48*
65	*0,04111*	*0,04311*	*0,08421*	*976736,22*	*950767,87*	*931462,61*	*906697,94*	*940886,22*
66	*0,05116*	*0,06166*	*0,11281*	*815258,23*	*799827,44*	*676444,17*	*663640,78*	*732407,92*
67	*0,03958*	*0,04163*	*0,08121*	*1209658,32*	*1179364,95*	*1149945,43*	*1121147,44*	*1164282,94*
68	*0,04966*	*0,04280*	*0,09247*	*601240,19*	*587823,62*	*697598,19*	*682031,40*	*638645,84*
69	*0,04499*	*0,05668*	*0,10167*	*792955,20*	*772471,22*	*629375,49*	*613117,17*	*692701,57*
70	*0,04856*	*0,05135*	*0,09991*	*826775,44*	*804794,08*	*781978,69*	*761188,33*	*793068,73*
71	*0,04725*	*0,04432*	*0,09158*	*754962,89*	*735460,34*	*804852,03*	*784060,72*	*769046,47*
72	*0,03477*	*0,03688*	*0,07164*	*961514,35*	*939457,62*	*906496,17*	*885701,54*	*922504,37*
73	*0,03945*	*0,04100*	*0,08045*	*860105,14*	*836022,87*	*827486,46*	*804317,49*	*831661,83*
74	*0,03490*	*0,03308*	*0,06798*	*1007552,57*	*986701,76*	*1063082,65*	*1041082,67*	*1023868,02*
75	*0,04232*	*0,04194*	*0,08426*	*801829,79*	*779379,18*	*808941,36*	*786291,63*	*794095,01*
76	*0,02544*	*0,04057*	*0,06601*	*1402235,03*	*1366011,85*	*879434,52*	*856716,57*	*1066978,29*

77	0,02654	0,02980	0,05634	1181959,43	1158175,14	1052763,81	1031579,29	1102422,41
78	0,04743	0,04102	0,08845	715373,03	695343,14	827183,86	804023,36	756485,32
79	0,04576	0,04581	0,09157	720837,68	707959,00	720082,33	707217,15	714023,84
80	0,06291	0,06291	0,12477	498667,90	488633,33	498667,90	488633,33	497773,27
81	0,02964	0,03940	0,06904	1334354,21	1305932,86	1003737,25	982357,94	1133485,54
82	0,02851	0,03147	0,05998	805566,53	786877,90	729791,88	712861,17	756926,20
83	0,05245	0,05050	0,10295	1006117,80	991634,11	1045047,58	1030003,48	1017873,52
84	0,04946	0,04812	0,09758	686025,06	666816,89	705071,02	685329,58	685682,08
85	0,05349	0,05097	0,10446	894908,37	872497,25	939297,34	915774,59	905088,99
86	0,04544	0,04495	0,09040	883539,72	860049,18	893170,55	869423,95	876520,09
87	0,04718	0,04227	0,08946	933077,46	917700,11	1041525,56	1024360,96	976212,50
88	0,04229	0,03994	0,08223	741834,25	726906,50	785447,52	769642,15	755331,97
89	0,04431	0,04823	0,09254	717815,09	699783,80	659403,51	642839,50	678744,67
90	0,03592	0,03728	0,07319	1161246,43	1139266,94	1118787,63	1097611,79	1128836,60
91	0,04794	0,04910	0,09704	707762,52	687945,72	691069,26	671719,86	689533,23
92	0,03109	0,04612	0,07721	1147598,96	1117953,66	773509,57	753527,92	912183,73
93	0,03971	0,04324	0,08295	885576,47	867249,89	813143,67	796316,06	839043,25
94	0,04214	0,04600	0,08814	1610579,20	1595704,15	1475494,75	1461867,32	1532968,53
95	0,03971	0,04110	0,08081	642740,34	627439,26	621018,00	606234,05	624165,72
96	0,04076	0,03907	0,07984	514977,74	501014,25	537292,44	522723,88	518768,68
97	0,05252	0,05262	0,10514	743130,03	731241,72	741604,91	729741,00	736428,64
98	0,02017	0,03975	0,05992	1934480,85	1903533,76	981865,72	966158,20	1292169,80
99	0,05881	0,06317	0,12198	1325588,02	1312916,63	1234134,87	1222337,69	1272097,54
100	0,05508	0,04913	0,10421	535204,29	525902,95	600102,96	589673,74	560876,79
101	0,02696	0,02808	0,05504	992650,11	971086,55	952744,76	932048,07	961727,53
102	0,03840	0,04102	0,07942	1004562,07	993832,93	940306,14	930263,28	966185,31

7.3.2 MOE Data Overview from NDE methods

#	MOEsw(PSI)	MOEtran (PSI)	MOEfull (PSI)
1	1363918,668	703582,64	581001,23
2	1318200,564	727214,60	837391,24
3	1043703,386	533069,10	577056,77
4	1223175,536	696669,96	751894,02
5	1004000,188	568217,04	818094,05
6	1463794,626	1235865,63	1760661,87
7	1557630,90	1168838,67	1273811,20
8	1618930,852	1098597,07	1095984,26
9	1159476,40	812802,34	764712,57
10	1128707,20	643851,13	657000,03
11	1710159,17	1090804,58	1255762,88
12	1243611,21	621755,03	714390,57
13	1624820,10	1099160,94	1274319,44
14	1421624,672	854062,67	1071264,07
15	1441913,526	807631,66	1313091,52

16	1585031,056	*1392319,77*	*1410403,21*
17	1570242,043	*1221129,95*	*1174717,76*
18	1435844,411	*740143,80*	*897849,74*
19	965673,5191	*597961,77*	*581869,55*
20	1636781,029	*904891,49*	*1220230,66*
21	1208763,817	*817829,47*	*1032521,69*
22	1712973,415	*1111486,79*	*1166103,64*
23	1538144,661	*1278512,47*	*1086343,63*
24	1280885,189	*794479,30*	*797804,65*
25	1168292,606	*782115,78*	*750520,57*
26	1238849,142	*734531,62*	*804778,51*
27	1592183,00	*1828335,56*	*1549192,00*
28	1250033,513	*952379,14*	*1005895,47*
29	1250420,212	*803603,69*	*892623,74*
30	1412915,133	*1429060,06*	*1085421,76*
31	1396691,682	*974669,60*	*859186,03*
32	1616123,311	*1162208,91*	*1331564,29*
33	1547924,761	*1135614,45*	*1021620,27*
34	1488859,351	*982793,75*	*1090729,51*
35	1441163,153	*806677,13*	*758801,66*
36	1577791,277	*1280996,21*	*1412322,67*
37	1285391,237	*1008617,83*	*812438,52*
38	1704720,149	*1185277,88*	*1242258,77*
39	1636684,938	*1165856,02*	*1122376,44*
40	1325137,228	*1025345,65*	*1129308,55*
41	1088499,787	*660226,11*	*709215,88*
42	1596739,612	*1085874,65*	*1286876,00*
43	1582038,469	*1179450,98*	*1154671,31*
44	1901193,602	*1344090,51*	*1310257,89*
45	1512279,567	*1126954,30*	*1078046,19*
46	1726627,129	*1234314,58*	*1264612,17*
47	1047373,648	*811600,95*	*690947,57*
48	1562922,053	*973748,93*	*1133234,77*
49	1455731,354	*1003872,64*	*1152844,79*
50	1133072,33	*805375,92*	*742299,16*
51	1152076,622	*682779,91*	*682478,93*
52	1060303,227	*814383,35*	*787055,85*
53	1160436,069	*705183,45*	*712152,25*
54	1579696,41	*971761,82*	*1053704,46*
55	1422521,728	*951567,93*	*866955,16*
56	1144319,974	*819363,36*	*487219,90*
57	1193509,492	*903637,60*	*931036,11*
58	1360853,365	*1020790,85*	*977212,50*
59	1336895,244	*853427,49*	*912311,03*
60	1326636,128	*863426,66*	*995659,46*

61	1129162,019	*773056,28*	*844133,93*
62	1374795,625	*1069096,88*	*1091456,95*
63	1218243,264	*932619,56*	*944104,65*
64	1239785,266	*888528,00*	*891866,48*
65	1207849,966	*942449,43*	*940886,22*
66	1045625,535	*721566,58*	*732407,92*
67	1126229,751	*1040104,00*	*1164282,94*
68	1028985,004	*652951,80*	*638645,84*
69	1239637,848	*829234,44*	*692701,57*
70	1074442,602	*828973,91*	*793068,73*
71	1171973,601	*791127,79*	*769046,47*
72	1398276,489	*1088705,93*	*922504,37*
73	1249873,825	*833902,89*	*831661,83*
74	1341583,667	*953284,73*	*1023868,02*
75	1140533,689	*905430,13*	*794095,01*
76	1222621,59	*783762,20*	*1066978,29*
77	1347887,882	*871791,16*	*1102422,41*
78	1052816,084	*601804,91*	*756485,32*
79	1036701,054	*800449,21*	*714023,84*
80	897022,6158	*463857,23*	*497773,27*
81	1513510,238	*1169777,55*	*1133485,54*
82	863887,1277	*1111438,15*	*756926,20*
83	1351949,31	*731132,06*	*1017873,52*
84	1086399,695	*657877,08*	*685682,08*
85	1367002,344	*1014929,30*	*905088,99*
86	1149519,964	*841696,82*	*876520,09*
87	1549494,962	*1484238,33*	*976212,50*
88	1138152,246	*730606,80*	*755331,97*
89	1238432,862	*805099,07*	*678744,67*
90	1324279,037	*1085015,03*	*1128836,60*
91	1105708,637	*735424,50*	*689533,23*
92	1041993,665	*854855,01*	*912183,73*
93	1276197,518	*794020,84*	*839043,25*
94	1708099,348	*1378632,91*	*1532968,53*
95	920390,0228	*502593,11*	*624165,72*
96	1072169,864	*603177,49*	*518768,68*
97	1339526,232	*1075826,83*	*736428,64*
98	1352405,302	*1086497,70*	*1292169,80*
99	1319111,073	*1438583,78*	*1272097,54*
100	1478554,287	*1501534,26*	*560876,79*
101	1445165,863	*822821,22*	*961727,53*
102	1212888,183	*865097,54*	*966185,31*

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