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MEASURING THE ADHESIVE BOND QUALITY OF VINYL ESTER-GLASS COMPOSITES ON NOVOLAK HMR TREATED WOOD

By

Leopold Eisenheld

Graduate Engineer University of Agricultural Sciences, Vienna, 1997

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Forestry)

The Graduate School

The University of Maine

December, 2003

Advisory Committee:

Douglas J. Gardner, Professor of Wood Sciences and Technology, Advisor

Stephen Shaler, Professor of Wood Sciences and Technology

Roberto Lopez-Anido, Assistant Professor of Civil Engineering

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Thesis Advisor: Dr. Douglas J. Gardner

An Abstract of the Thesis Presented
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The objectives of this research were to 1) reduce the drying time of novolak-based HMR coupling agent, 2) reinforce wood samples with E-glass/vinyl ester resin composite using the SCRIMP™ process, 3) evaluate the durability and strength properties of the FRP-wood composites, and 4) evaluate the bonding strength of wood-to-wood bonding using vinyl ester resin.

To reduce the drying time of HMR-treated wood laminates, a randomized complete three factorial experiment was used to evaluate five HMR drying times, two HMR spread rates, and two HMR solids contents. The experiment evaluated the sensitivity of the HMR treatment process to accelerated drying. The analysis resulted in the reduction of the HMR drying time to 15-20 minutes instead of the 18-24 hours usually required for epoxy resin bonded hard maple laminates. The HMR treatment process is not sensitive to changes in the HMR spread rate or the HMR solids content, but is significantly effected by the HMR drying time.

The accelerated drying of HMR was applied to wood samples reinforced with E-glass/vinyl ester resin using the SCRIMP™ process. A technique was developed to apply the SCRIMP™ process for the reinforcement of small scale wood members such as glulam billets and boards. These samples were evaluated with typical screening tests ASTM D 905 standard test method for strength properties of adhesive bonds in shear by compression loading and the ASTM D 2559 standard specification for adhesives for structural laminated wood products for use under exterior (wet use) exposure conditions. The analysis resulted in the reduction of the total production time of wood-FRP composites by 18-24 hours. The FRP-wood composites had a high shear strength and a high percentage of wood failure.

Wood-to-wood bonding using vinyl ester resin was not successful. Typical bonding parameters such as clamping pressure, spread rate, opening time, etc. had no effect on the bonding performance of wood-to-wood vinyl ester bonded laminates. The vinyl ester resins used failed most of the bonding tests. It is recommended to evaluate vinyl ester resins that are specifically promoted for wood-to-wood bonding.

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Many thanks go to Composite One for the donation of vinyl ester resins. Within The University of Maine, the author wishes to thank several key people as well. Don Strong for the use of his facilities. Brad Weiland for the help with operating the mechanical testing equipment. William Tze, who has always been there with support and empathy.

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Chapter 1

FRP-WOOD COMPOSITES AND HMR COUPLING AGENT

1.1. Introduction

The reinforcement of structural timber using fiber reinforced polymers (FRPs) is being utilized to a greater extent in industrial applications of wood composites (Lopez-Anido *et al.* 2002a, Lopez-Anido *et al.* 2002b, Lopez-Anido and Karbhari 2000, Battles *et al.* 2000). The FRP reinforcement acts as load bearing unit and large-scale structures can be fabricated with higher bending strength stiffness and lower weight (Gardner *et al.* 1994). Lopez-Anido *et al.* (2002a) state three general procedures to reinforce wood with FRP composites, which are (a) bonding of consolidated laminates, (b) wet-lay up of fabrics, and (c) resin infusion of fabrics by vacuum. All these types of FRP composite consist primarily of two parts, fibers embedded in a polymeric matrix (Daniel and Ishai 1994, Berins 1991). Fibers may be carbon, glass, or aramid (Berins 1991), and matrix polymers may be epoxy, polyurethane, phenol-formaldehyde, or vinyl ester (Berins 1991, Schwartz and Goodman 1982). Consolidated materials are usually bonded to wood with adhesive derived from the same polymers, as the matrices for the FRP. Reinforcements such as wet-lay up and resin infusion are applied to wood *in situ*. In these cases, the polymer matrices act as an adhesive.

All 3 general types of FRP composites stated above were evaluated successfully by Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b), and Lopez-Anido *et al.*

(2000). Consolidated materials manufactured using the pultrusion process were tested by Gardner *et al.* (1994). All researchers tested both strength and durability properties of FRP-wood composites.

Many of the adhesives used for bonding FRP to wood don't adhere properly to wood, whereas commonly used structural adhesives, such as melamine-formaldehyde, phenol-formaldehyde and resorcinol-formaldehyde (Marra 1992), often can't be used for bonding FRP's to wood. To improve the bonding strength of FRP to wood, a coupling agent is used. For FRP-to-wood bonding the most commonly used coupling agent, also referred to as a primer, is hydroxymethylated resorcinol (HMR). HMR improves the bonding strength of epoxy resins (Vick *et al.* 1995, Vick and Okkonen 1997, Vick *et al.* 1998), but also improves the bonding of vinyl ester resin (Lopez-Anido *et al.* 2000), and phenol-resorcinol-formaldehyde (PRF) resin on preservative treated southern pine (Vick 1995).

HMR is hypothesized to act as a link between the wood substrate and the resin matrix. The linkages are thought to range from covalent to ether and hydrogen bonding (Vick and Okkonen 1997) depending on the chemical functional groups comprising the involved reactants. Gardner *et al.* (2000) found that HMR-treated wood has an increased polar surface energy, which enhances the interaction between HMR-treated wood surface and the adhesive. This may promote both strong secondary interactions and the possible formation of covalent bonds during adhesive curing.

The HMR coupling agent is applied to the wood surface as an aqueous solution with low solids content (5 %) and is analogous to a low molecular weight resorcinol-formaldehyde resin. It contains four main components, which are resorcinol,

formaldehyde, sodium hydroxide and water (Table 1). At this moment, two types of HMR have been evaluated in laboratory studies. For wood-to-wood bonding using epoxy adhesives, the original version of HMR was used by Vick *et al.* (1995), Vick and Okkonen (1997), and Vick *et al.* (1998). In these studies, the HMR solution was allowed to react for 4 hours at room temperature. After 4 hours, the solution was applied onto a freshly planed wood surface. Because of the amount of water contained in the HMR solution (95 %) the HMR-treated surface needs to dry out prior to adhesive application. During drying, water evaporates from the wood surface while the resorcinol and formaldehyde react. A drying time of 18 to 24 hours used at ambient conditions to bond non-aqueous adhesives, such as epoxy resins, makes HMR commercially cumbersome to use, too. Care of freshly HMR-treated wood is required, because contamination with e.g. dust or chemical vapor can decrease the effectiveness of the HMR.

To reduce the reaction time of the HMR solution, Christiansen *et al.* (2000) developed a novolak-based HMR coupling agent that is able to react within one hour of mixture at ambient temperature. This circumstance makes the coupling agent user-friendlier. But still, the 24-hours drying time of the HMR treated wood surface needs to be reduced to be more attractive to commercial manufacturers of wood composites.

1.2. Research Objectives

The research objectives of this thesis were as follows.

- The reduction of the HMR drying time and the simulation of an industrial process that uses an HMR-resin system.

- Developing a technique to use SCRIMP™ for reinforcement of structural wood members.
- The evaluation of the bondline quality of HMR-treated wood members reinforced with the SCRIMP™
- The evaluation of the bondline quality of wood-to-wood bonding using the HMR-vinyl ester resin system.

This thesis focused mainly on the interphase of wood-to-wood and FRP-to-wood bonding. Screening tests were used for selecting appropriate levels for the primer-adhesive system. The experiments had the goal of developing the knowledge base for industrial application of HMR treatment in FRP-wood bonding. As mentioned in the Introduction, for many wood-FRP composites the use of HMR is necessary. Without HMR, the bonding of FRP to wood is poor and the bond line delaminates during exposure to wet conditions. On the other hand, the use of HMR makes the product more expensive. For a viable industrial application of HMR, a long drying time is unacceptable. A shorter drying time of a few minutes, possibly a few seconds, could improve the industrial use of HMR. Decreasing the drying time of HMR could make possible the commercially viable industrial production of reinforced structural parts. A proposed process using HMR priming to produce reinforced beams is shown in Figure 1. In step 1, finger-jointed lumber is laminated to beams by using a commercial adhesive for either interior or exterior. The press time is often longer than eight hours, and therefore, beams are stored before HMR is applied to the wood surface. Once numerous beams are produced, a planer and HMR coater are used. The beam can be planed on four

longitudinal surfaces followed by HMR-coating of the surface that is being reinforced. The HMR coating could be done with roller or spray coater (step 2). After HMR treatment, extreme care must be taken of the beams. A fresh HMR-treated surface should not be touched until the FRP reinforcement is applied. Any contamination (dust, grease, etc.) lowers the bonding strength between the wood and FRP. After coating, the beam may either be stored in clean storage, or can be run through a drying apparatus (step 3). Finally, in step 4, the FRP reinforcement is applied to the beam.

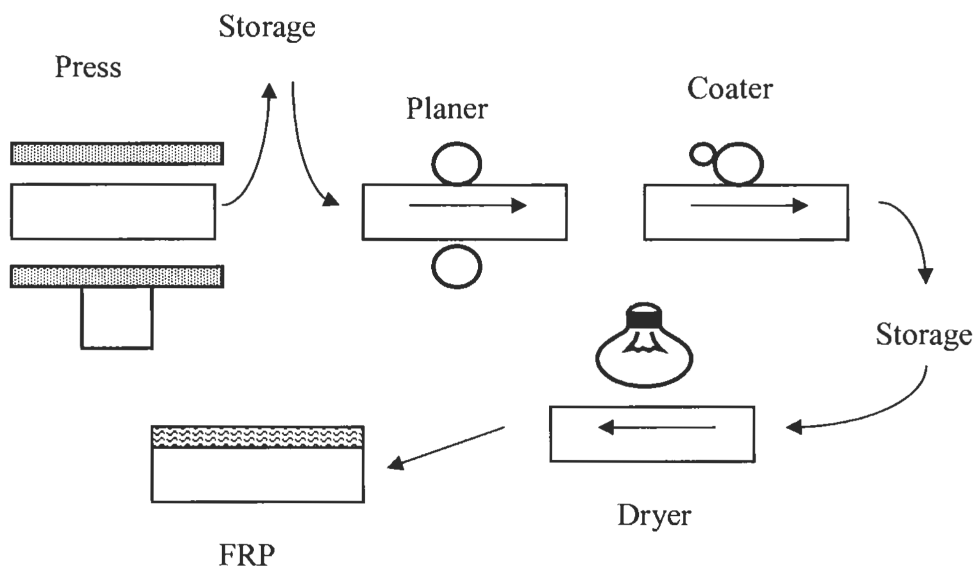

Figure 1. Proposed Industrial HMR Drying Process

The 1st objective was to accelerate the drying of HMR using heat emitted from infrared (IR) heating lamps. To solve this problem a screening test was conducted. This screening test utilized 3 factors, which were (1) different HMR drying times, (2) different HMR spread rates, and (3) different HMR solid contents. Each factor contained a few levels to determine the response sensitivity of the HMR treatment. The experiment was conducted on hard maple (*Acer saccharum*) treated with HMR solution according to its

factor combination. The HMR treated boards were dried by heat emitted from IR lamps. From the HMR treated boards, 2-layer laminates were produced using epoxy resin as an adhesive. The shear strength and percentage wood failure of the laminates were tested according to ASTM D 905 (1994) and were used for evaluation of the best HMR-reaction conditions. This experiment contributed to the knowledge required to develop an industrial process using HMR as a wood primer. Therefore, it was designed as a simulation of a proposed industrial process.

The 2nd objective of this thesis was to develop a method to use Seemann's resin infusion molding process (SCRIMP™) for reinforcing structural wood members such as beams, poles and panels. SCRIMP™ belongs to the group of reinforcements where fabrics are resin infused using a vacuum. An entire chapter of this thesis covers a detailed description of this reinforcement process. Advantages and disadvantages of SCRIMP™ were evaluated to provide the reader with all the necessary application information.

The 3rd objective of this thesis was to evaluate the bondline quality of HMR-treated structural wood members reinforced with SCRIMP™. The evaluation of the bondline quality of a primer-resin-FRP system relies on two tests. To evaluate the bonding strength of the system, shear blocks are produced and are tested in shear by compression loading. This test is based on the standard test method ASTM D 905 (1994) and evaluates not only the shear strength; it also estimates the percentage of wood failure at the bondline interphase. Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b), and Lopez-Anido *et al.* (2000) used this test as a criterion for the evaluation of FRP-wood composites. For this reason, an experiment was conducted to evaluate the bonding strength respectively the wood failure of HMR-treated wood laminates reinforced with E-

glass/vinyl ester resin using SCRIMP™. Another widely used test to evaluate the bonding quality of FRP-wood composites is the test for resistance to delamination during accelerated exposure to wetting and drying according to ASTM D 2559 (1998). In this test, wood-FRP composites are repeatedly exposed to cycles of water soaking, steaming and drying. Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b), and Lopez-Anido *et al.* (2000) used this test as a criterion for the evaluation of FRP-wood composites, too. For this reason, an experiment was conducted to evaluate the durability of HMR-treated wood laminates reinforced with E-glass/vinyl ester resin using SCRIMP™. Both the measurement of the bond quality (shear strength and wood failure) and the determination of delamination, were conducted on novolak-based HMR-treated wood that was reinforced with SCRIMP™. The standard HMR drying procedure (24 hours at 23±2°C and 65 % relative humidity) was used to determine basic properties of the HMR treatment. Both, the adhesive bond properties and the results of the IR-heat accelerated experiment on HMR drying were then used for developing a heat-accelerated reinforcement method using SCRIMP™. An experiment was conducted in which wood laminates were treated with HMR followed by IR-drying. The heat-dried wood laminates were reinforced using SCRIMP™ and the shear strength and percentage of wood failure were determined. This experiment simulated an industrial process of reinforcing structural wood as shown in Figure 1. Furthermore, this experiment acted as a link between the first two main objectives of this thesis, the reduction of the HMR drying time and one type of wood-FRP reinforcement.

The 4th objective of this thesis was to evaluate the bondline quality of wood-to-wood bonding using the HMR-vinyl ester resin system. For wood-FRP composite using

SCRIMP™ Derakane epoxy vinyl ester resin 411-C-50 from Dow Chemical Company, Inc., is commonly used. Two out of four wood-FRP composites tested by Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b) used this resin. The low cost of vinyl ester resin ($ 3.30/kg) compared to epoxy resin ($ 12.50/kg) makes it very attractive for wood-FRP bonding applications. The successful tests on SCRIMP™ by Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b) showed the possibility of using vinyl ester resin for bonding pre-consolidated FRPs to structural wood members. A series of experiments was conducted to select an appropriate vinyl ester resin for wood-to-wood bonding. The assumption here was that if vinyl ester resin can be used for wood-to-FRP bonding, it must be possible to use it for wood-to-wood bonding, too. In these tests, the shear strength and percentage of wood failure of wood laminates were tested according to ASTM D 905 (1994) and were used to select the most appropriate vinyl ester resin type.

In conclusion, this thesis focused especially on the interphase of wood-to-wood and wood-to-FRP bondings. This thesis should help to realize a commercially viable industrial process of reinforcing wood using the SCRIMP™ technology. The solution of this problem was attacked stepwise. First, the optimization of an effective HMR treatment process was solved. Second, the optimization of the SCRIMP™ technique and the determination of the bondline quality of SCRIMP™-reinforced wood members was realized. With the information provided in this thesis, the reader will be able to decide whether the HMR-SCRIMP™-reinforcement system is appropriate for wood composite manufacture.

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Chapter 2

EXPERIMENT TO REDUCE THE HMR DRYING TIME

2.1. Introduction

As mentioned in Chapter 1, research has been carried out on HMR treatment. Vick (1995) and Vick *et al.* (1995) carried out experiments on 5 % aqueous HMR solutions to improve the durability of wood composites. The tests were based on the percentage of delamination measured on test billets after exposure to cycles of water-soaking, drying and steaming according to ASTM D 2559. The researchers measured an improvement of the durability of wood composites due to HMR treatment.

In 1997, Vick and Okkonen could improve the shear strength and the durability of epoxy bonding using several types of epoxy adhesives and four wood species. They state that without the HMR coupling agent, none of the epoxy adhesives had sufficient delamination resistance to meet ASTM requirements on any tested wood species. Vick *et al.* (1998) determined the optimum reaction time of the HMR solution is 3-8 hours before priming the wood substrate. In addition, the heat of reaction and chemical linkages of the polymerizing HMR solution were investigated.

In 2000, Christiansen *et al.* published a paper on a novolak-based HMR solution which doesn't require a 3-8 hours reaction time. The new HMR solution was found to be storable for an infinite time and the reaction time was reduced to 0.5-1 hour. The durability performance of the novolak-based HMR met the requirements of ASTM D 2559. Gardner *et al.* (2000) reported that HMR enhanced wood-adhesive bonds by

promoting secondary chemical interactions and the possible formation of covalent bonds during adhesive curing. In the years between 2000 and 2002, Lopez-Anido *et al.* (2000), Lopez-Anido *et al.* (2002a), and Lopez-Anido *et al.* (2002b), used HMR as a primer for reinforcing structural laminated timber (glulam) with fiber reinforced polymers (FRP). Now, it was possible to improve the bond quality of FRP-to-wood bonds using vinyl ester resin or epoxy adhesives.

In all research mentioned above, the HMR coupling agent had to be dried for at least 18-24 hours before the adhesive was applied to the wood. Drying was generally done in a conditioning chamber under standard drying conditions such as 23±2°C and 65 % relative humidity. Those reaction conditions elevate the production complexity of wood composite manufacture and make them commercially unattractive. The industrial use of HMR demands a shorter HMR drying time to make the wood composite cost and process efficient.

In this chapter, the experiment aimed to reduce the HMR drying time using infra-red (IR) heat emitted from lamps. In addition, the experiment evaluated the sensitivity of the entire HMR-adhesive system. Besides the HMR drying time, the effects of two other factors, the HMR spread rate and the HMR solids content, were evaluated. The most appropriate type of HMR available, novolak-based HMR, was used to optimize the bonding process. Furthermore, the experiment utilized a quick and accurate technique to evaluate the bonding performance. The most widely used test that serves these objectives is the determination of both the shear strength and percentage of wood failure according to ASTM D 905 (1994). In this standard test, wood laminates shear block samples are tested in compression. ASTM D 905 (1994) uses as a reference wood species hard maple

(*Acer saccharum*). The experiment was originally designed to use vinyl ester resin as an adhesive. This resin is successfully used in the SCRIMP™ technology. Research to be described in Chapter 3 had shown that vinyl ester resin couldn't be used for wood-to-wood bonding. Therefore, FPL-1 epoxy resin was used.

2.2. Materials and Testing Equipment

2.2.1. Coupling Agent

For this experiment, novolak-based hydroxymethylated resorcinol (HMR) coupling agent was used. Novolak-based HMR has two chemical states and the mixing procedure is divided into two steps. The first step of mixing provides a novolak-based HMR solution. The second step transfers the coupling agent from the novolak status to the activated status. The notation of the coupling agent in the novolak stage is determined as novolak-based HMR coupling agent, whereas, the activated stage is called activated, novolak-based HMR coupling agent (n-HMR) (Christiansen *et al.* 2000).

2.2.1.1. Novolak-based HMR and n-HMR

Christiansen *et al.* (2000) developed the novolak-based HMR coupling agent and tested different formaldehyde-resorcinol (F/R) ratios from 0.23 to 0.46 for the novolak stage. In this thesis, a F/R ratio of 0.39 was used.

The mixing procedure used for n-HMR at 5 % solids content is described as follows. For the novolak status 3.34 g of crystalline resorcinol were dissolved in 90.43 g of deionized water by using a magnetic stir bar mixer. After stirring the solution for approximately 5 minutes, 2.44 g of a 3-molar sodium hydroxide solution were added to the solution. This solution was stirred for 5 minutes. Adding 0.95 g of formaldehyde solution, followed by stirring for 5 minutes, concluded the preparation of novolak-based HMR solution. The novolak-based HMR was stored at ambient conditions for at least three days, but no longer then six days. Before the n-HMR coupling agent was applied to the wood, the final amount of formaldehyde was added to the solution. 2.84 g of formaldehyde solution were added to the solution followed by stirring for 5 minutes. At this stage, the F/R ratio was increased from 0.39 to 1.54 and the HMR solution was activated (n-HMR). After adding the final amount of formaldehyde solution, the pH was determined. The pH was adjusted by adding 3-molar sodium hydroxide solution to the HMR solution. The pH was held in a range between 8.5 and 9.0. This solution was allowed to react for one hour. At the end of the reaction time, 0.5 g of dodecyl sulfate sodium salt were added to the n-HMR solution to improve the wetting of the wood surface. Within the next 1-3 hours the n-HMR solution was applied to wood. Table 1 shows the ingredients for the n-HMR solution at 5 % solids content.

Table 1. Ingredients of n-HMR

Ingredients	Amount of Chemical (g)
Crystalline Resorcinol	3.34
Deionized Water	90.43
3-Molar Sodium Hydroxide Solution	2.44
Formaldehyde Solution (37.1% Formalin)	
For Novolak Stage	0.95
For Final Activation Stage	2.84
Dodecyl Sulfate Sodium Salt	0.50

2.2.1.2. HMR Solids Content

For this study, HMR solids content at the 5 % level and at the 10 % level were used. The mixing procedure as described in section 2.1.1 was used for both solutions. Table 2 shows the ingredients for both HMR solutions.

Table 2. HMR Solids Contents

HMR Ingredients	HMR Solids Content	
	5 % (g)	10 % (g)
Crystalline Resorcinol	3.34	6.68
Deionized Water	90.43	80.86
3-Molar Sodium Hydroxide Solution	2.44	4.88
Stage 1: Formaldehyde Solution (37 % Formalin)	0.95	1.90
Stage 2: Formaldehyde Solution (37 % Formalin)	2.84	5.68
Dodecyl Sodium Sulfate Salt	0.50	0.50
Total Weight	100.50	100.50

The following chemicals were used to make n-HMR coupling agent.

- Sodium hydroxide pellets (NF/FCC) from Fisher Scientific, Pittsburgh, PA.
- Resorcinol (1,3-benzenediol), approx. 99% from Sigma Chemical Co., St. Louis, MO.
- Lauryl sulfate (sodium dodecyl sulfate), sodium salt, approximately 95% based on total alkyl sulfate content from Sigma Chemical Co., St. Louis, MO.
- Formaldehyde 37% solution (formalin), ACS reagent from Sigma Chemical Co., St. Louis, MO.

2.2.2. Wood Species and Wood Samples

The experiment was conducted on flat-sawn hard maple (*Acer saccharum*). The boards were stored at standard conditions (24ºC, 65 % RH) for at least eight weeks. The dimensions of the lumber was 3000 x 125 x 19 mm (length x width x thickness). The lumber grade was "select" according to the hardwood lumber grades of the National Hardwood Lumber Association (NHLA) (Haygreen and Bowyer 1989). KARAM's Hardwood & Millwork from Bangor, ME, supplied the lumber.

2.2.3. Epoxy Adhesive

The heat-accelerated experiment to reduce the drying time of HMR was conducted on epoxy adhesive. The adhesive is also known as FPL-1 epoxy resin. Table 3 shows the ingredients. According to Vick and Okkonen (1997), this adhesive was derived from the reaction of bisphenol-A with epichlorohydrin to form a diglycidether of bisphenol-A (DGEBA). The DGEBA epoxy resin is also known as D.E.R. 331. The mixing procedure was as follows. 9.9 g of benzyl alcohol were added to 79.3 g D.E.R. 331 epoxy resin. This solution was stirred for 2 minutes. 4 g of hydrophobic fumed silica were added to the solution followed by stirring for 2 minutes. 8.8 g of triethylenetetramine (hardener) were added to the solution followed by stirring for 2 minutes. Within the next 10 minutes, the adhesive was applied.

Table 3. Ingredients of FPL-1 Epoxy Resin

Ingredients	Amount of Chemical (g)
D.E.R. 331 Epoxy Resin	79.3
Benzyl Alcohol	9.9
Hydrophobic Fumed Silica	4.0
Triethylenetetramine	8.8

The following chemicals were used.

- D.E.R.* 331 Epoxy resin from The Dow Chemical Company, Midland, MI
- Benzyl alcohol, 99 %, from Aldrich Chemical Company, Milwaukee, WI
- Triethylenetetramine, tech., 60 %, from Aldrich Chemical Company, Milwaukee, WI
- Hydrophobic fumed silica from Aldrich Chemical Company, Milwaukee, WI

2.2.4. Apparatus for Drying n-HMR-treated Surfaces

HMR-treated surfaces were dried in an apparatus shown in Figures 2-4. The apparatus was made from plywood boards having a thickness of 12.5 mm. The dimensions of the apparatus were 650 x 250 mm (A x B). The specimen (1) was placed under 4 infrared (IR) lamps (2) in a vertical distance of 230 mm (C). The lamps were mounted at a horizontal distance of 25 mm to one another. The total span covered by the lamps was 650 mm. The emitted infrared light heated the surface of the specimen, and the water in the n-HMR solution evaporated. A laser beam temperature measurement device was spotted to the HMR-treated surface and the Raynger® unit (3) collected the emitted, reflected and transmitted energy from the sample surface. The distance from the

measuring point at the sample surface to the thermometer unit was about 400 mm. Both hot air and evaporated HMR solution were able to leave the apparatus through vents on the top (4).

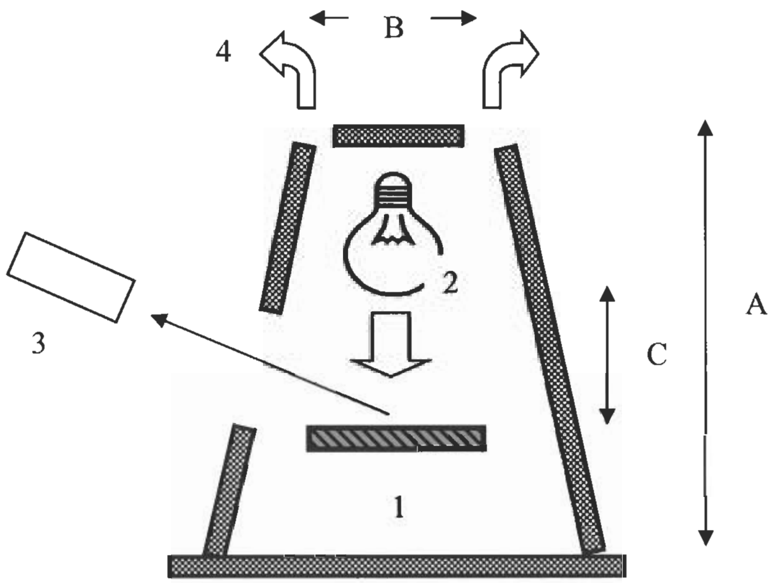

Figure 2. **Function of the HMR Drying Apparatus**

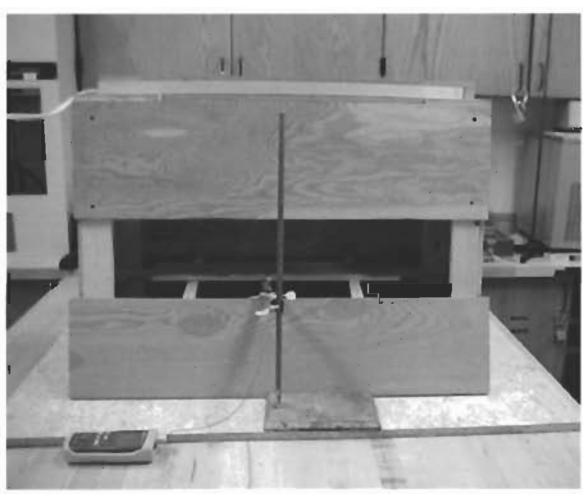

Figure 3. **HMR Drying Apparatus**

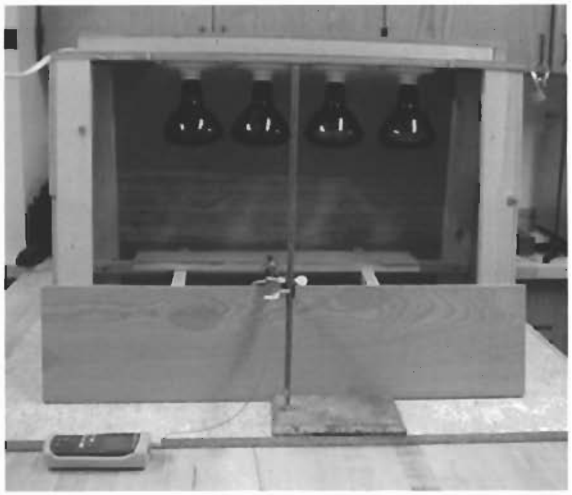

Figure 4. HMR Drying Apparatus with Removed Hood Board

The drying apparatus contained the following equipment.

- 4 x 250W IR heat lamps, medium base IR40 (125 mm diameter) from Phillips Lightning Co., Somerset, NJ.
- 4 x Porcelain lamp holder with leads, medium base-keyless, 660W 250V, from Leviton Manufacturing Co., Inc., Little Neck, NY.
- Wire NM-B-12/2-Cu-WG-1000S/R from Standard Electric Co., Bangor, ME.
- Noncontact Thermometer Raynger® ST60 ProPlus™ Standard, from Raytek Corporation, Santa Cruz, CA.

2.2.5. Press Clamps

Shear block laminates were bonded in press clamps (Figure 5). Eight press clamps were used to produce sixteen wood laminates per day. The press clamps were made from mild steel. The press plates had the dimensions of 300 x 180 x 12.5 mm (length x width x

thickness). Four threaded rods were used as the clamping device. Each rod had a diameter of 12 mm. The rods were mounted in a longitudinal distance of 150 mm and in a cross-distance of 150 mm. For wood laminates having a clamping area of 250 x 115 mm a clamping pressure of 350 kPa was applied.

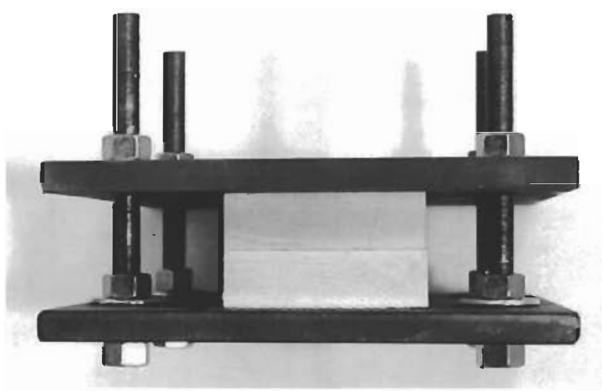

Figure 5. Press Clamp with Hard Maple Laminate

2.2.6. INSTRON Testing Frame

The shear strength (ASTM D 905, 1994) was determined on an INSTRON testing frame (Figure 6). The following testing frame and data acquisition system was used.

- Servo Hydraulic Universal Testing System (INSTRON Model 8801), INSTRON Corporation, Canton, MA.
- Material Tests Control System (INSTRON Fast Track 8800), INSTRON Corporation, Canton, MA.

Figure 6. **INSTRON Testing Frame**

2.2.7. pH Meter

The pH of the HMR solutions was measured using the following pH meter.

- Orion Benchtop pH/ISE Meter, Model 420A from Orion Research, Inc., Beverly, MA

2.3. Methods

2.3.1. Experimental Design and Factors of the Experiment

The experiment was conducted as a completely random design in a factorial arrangement (Steel *et al.* 1997, Snedecor and Cochrane 1989, Little and Hills 1978) and examined following factors.

Factor A: HMR Drying Time

1 5 minutes at ~45°C

2 10 minutes at ~55°C

3 15 minutes at ~60°C

4 20 minutes at ~65°C

5 24 hours at 23±2°C and 65 % relative humidity (standard conditions)

Factor B: HMR Spread Rate

1 146 g/m^2

2 220 g/m^2

Factor C: HMR Solids Content

1 5 %

2 10 %

The HMR drying temperature (Factor A) increased with increasing HMR drying time. It was investigated that the surface temperature of the drying HMR-treated surface is not constant over time. The average temperature of the drying HMR-treated for each HMR drying time varied between 45-65ºC. Totally, twenty treatment combinations were tested. Each treatment combination was replicated seven times, giving a total number of 140 laminates. A single laminate contained of two layers of hard maple boards having the dimensions of 250 x 115 x 15 mm (length x width x thickness). The following linear additive model was applied.

Equation 1. Linear Additive Model for the 3-Factor Factorial

$$Y_{ijkl} = \mu+\alpha_i+\beta_j+\gamma_k+(\alpha\beta)_{ij}+(\alpha\gamma)_{ik}+(\beta\gamma)_{jk}+(\alpha\beta\gamma)_{ijk}+\epsilon_{ijkl}$$

The equation's components were following.

Y_{ijkl}	observation (response variable)
μ	mean of the sample population
α_i	average effect of the HMR drying time
β_j	average effect of the HMR spread rate
γ_k	average effect of the HMR solids content
$(\alpha\beta)_{ij}$	interaction between HMR drying time and HMR spread rate
$(\alpha\gamma)_{ik}$	interaction between HMR drying time and HMR solids content
$(\beta\gamma)_{jk}$	interaction between HMR spread rate and HMR solids content

$(\alpha\beta\gamma)_{ijk}$ interaction between HMR drying time and HMR spread rate and HMR solids content

ϵ_{ijkl} experimental error, which is not explained by the model

2.3.2. Response Variables of the Experiment

A single treatment combination provided four response variables described as follows.

- Bondline shear strength at standard conditions
- Bondline shear strength for the water-soaked condition
- Bondline wood failure percentage at standard conditions
- Bondline wood failure percentage for the water-soaked condition

According to ASTM D 905 (1994), the shear strength and the percentage of wood failure were measured on shear block samples. Six shear blocks were cut from a single laminate. Three shear blocks were tested at standard conditions, whereas three shear blocks were tested under water-soaked conditions. The three shear block strength (wood failure) values of each condition were averaged. In the analysis of variance (ANOVA), this mean was used to determine the treatment effect of the particular treatment combination. By treatment separation, the four degrees of freedom of factor A (HMR drying time) were broke down to four single degree of freedom F-tests. Following treatment separation was analyzed using contrast coefficients.

- standard HMR drying time (24 hours) vs. IR drying times (5-20 minutes)
- 5 minutes-HMR drying time vs. 10-to-20 minutes- HMR drying times
- 10 minutes-HMR drying time vs. 15-to-20 minutes-HMR drying times
- 15 minutes-HMR drying time vs. 20 minutes-HMR drying time

In addition to the treatment separation, the treatment means were analyzed using Duncan's Multiple Range Test (DMRT). DMRT is one of the most used multiple mean comparison tests used by entomologists (Jones 1984, Chew 1976). A α level of 0.05 was used. SAS® software (SAS Institute Inc. 1985) was used for separately analyzing each of the four variables. The total number of shear blocks was 840, where 420 were tested at standard conditions and 420 were tested for the water-soaked condition.

2.3.3. Production Steps of Lamination

The sequence of the production of a single laminate and the further production of six shear blocks is listed below.

A. Preparation of the coupling agent

1. Preparation of novolak-based HMR coupling agent (stage 1)
2. Storage of the coupling agent
3. Preparation of n-HMR (stage 2)
4. Reaction of n-HMR

B. Preparation of the laminate boards

1. Surface planning of the laminate boards

2. Storage of the laminate boards

C. Application of n-HMR to the laminate boards

D. Drying of n-HMR-treated laminate boards

1. Drying of control specimens at standard conditions

2. Drying of n-HMR-treated wood laminate boards under IR heat

D. Storage of the laminate boards

E. Preparation of the epoxy resin

1. Mixing of the adhesive

2. Application of adhesive

F. Laminate Bonding

G. Storage of laminates at standard conditions

H. Cutting of the shear blocks

I. Storage of the shear blocks at standard conditions

J. Measurement of shear strength and percentage of wood failure on the INSTRON testing frame.

The experiment was conducted on flat-sawn hard maple lumber. Sixteen laminates having two layers were bonded each day. A splitting procedure (Figure 7) was used to provide a natural variation between laminate boards. The splitting procedure minimized the amount of waste wood (marked with pattern in Figure 8) due to scalloped surface caused by the planer. In step 1, between six and eight boards (length 3000 mm)

were split into 12-16 boards (length 1000 or 2000 mm). In step 2, the half of these boards was planed and the scalloped ends (~120 mm on each side) were discharged. In step 3, from the planed boards 32 laminate boards (250 x 115 x 15 mm) were cut.

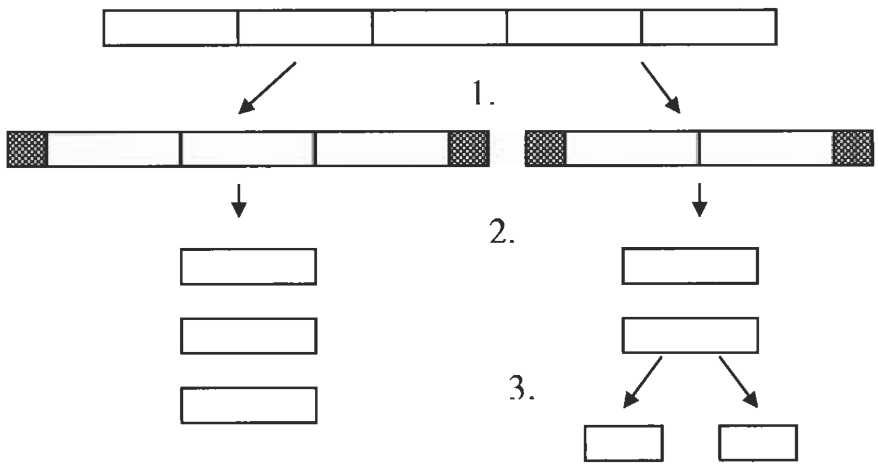

Figure 7. Splitting Procedure of Lumber Boards

The boards were planed with a feeding speed of 10 m/min. After planing, the boards were stored at room conditions for no longer then four hours. All possible treatment combinations were assigned with random numbers provided by SAS®. The following random numbers SAS® procedure was used.

```
DO I=1 TO 140;
X=INT(140*RANUNI (I))
```

In this procedure, X was the random number. The laminate treatment combination having assigned the lowest random number was produced first. This procedure was continued until all 140 laminate treatment combinations were produced. Before reacting

the n-HMR for one hour as described in Chapter 2.2.1.1, the pH of the HMR solution was measured using the pH meter. Sometimes, the pH of the novolak solution dropped after the storage time of 3-6 days. After adding the final amount of formaldehyde solution, the pH was measured and if necessary a 3-molar sodium hydroxide solution was added until a pH between 8.5-9.0 was attained. Immediately after reacting the n-HMR, two boards of the first laminate were treated with the n-HMR solution according to its treatment combination. Immediately after HMR treatment, the boards were placed beneath the IR heat lamps. When the first laminate was almost finished drying, the 2nd laminate was treated with HMR. During the drying of the 2nd laminate, the epoxy resin was prepared. In the meantime, the 1st laminate was kept on the top board of the drying apparatus to avoid cooling down. Immediately after drying, the adhesive was applied and the two laminates were bonded in the press-clamp. In a single press cycle, two laminates were bonded. The spread rate of epoxy resin was 500 g/m^2 per single bondline. The clamping pressure was 350 kPa. The laminates were allowed to cure overnight. The bonded laminates were stored under standard conditions (23±2°C and 65 % RH) for at least three days. From each laminate six shear blocks were cut. The size of the shear block specimens was according to ASTM D905 (1994). The shear blocks were kept one day at standard conditions.

2.3.4. Testing

The shear strength was determined using the INSTRON testing frame. The loading was in shear by compression (Figure 8) and the loading speed was 1.27 mm/min. The shear strength and percentage of wood failure was determined for two conditions. The shear strength at standard conditions was determined at 23±2°C and 65 % RH. The shear strength for the water-soaked conditions was determined after soaking in water under vacuum (635 mm mercury) for 20 minutes followed by soaking in water under 520 kPa pressure for another 20 minutes. After determining the shear strength, the percentage of wood failure (patterned in Figure 8) at the shear area was estimated to the nearest 5 %. Figure 8 shows on the left side the loading direction of a shear block, and on the right side the shear area (50 x 42 mm).

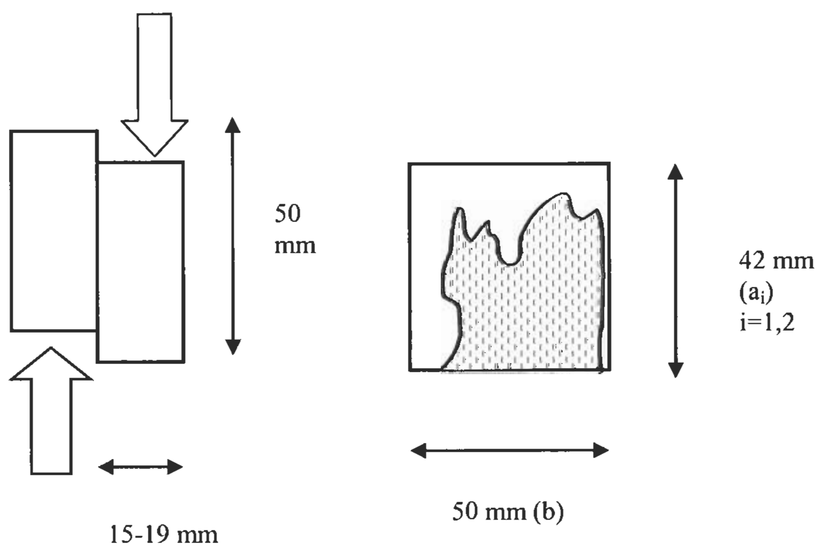

Figure 8. Shear Block Loading (Left Side) and Shear Area (Right Side)

The shear area was measured using a caliper. The shear strength was calculated using following formula.

Equation 2. Calculation of the Shear Strength

$$P = \frac{F}{A}$$

P apparent shear strength (Pa)

F Load to breakage (N)

A shear area (m^2)

The shear area was not exactly rectangular. Due to the natural inaccuracy of table saws, the shear area was more like a parallelogram. The length of the shear area in longitudinal direction (a_i in Figure 9) of the wood fibers was not the same on both sides. The length of the shear area in tangential direction (b) of the wood fibers was indeed the same on both sides. Therefore, the area was calculated using Equation 3.

Equation 3. Calculation of the Shear Area

$$A = \frac{a_1 + a_2}{2} \cdot b$$

a_1 length 1 of the shear area in longitudinal direction (m)

a_2 length 2 of the shear area in longitudinal direction (m)

b length of the shear area in tangential direction (m)

2.4. Results and Discussion

The experiment provided successful results and simulated a proposed industrial process as shown in Figure 1. The entire process beginning from planing of the surface of the laminates up to bonding in the press clamps was carried out in a manner of an industrial process. After planing, the laminates were treated with n-HMR within four hours. It took about two minutes to apply HMR to the two boards of a single laminate. Immediately after HMR application, the laminate was placed beneath the IR lamps. In an industrial process the laminate would be fed from the HMR coating station into the HMR drying station in the same period of time. The drying step simulated the industrial drying station. After HMR drying, the laminate was kept over heat until a 2^{nd} laminate was dried. This kept the temperature of both laminates elevated until the epoxy adhesive was applied to the bondline. The laminate leaves the HMR drying station and is fed into the adhesive-coating station. After adhesive application, the laminates were bonded in the press clamp. At that time, the laminate temperature was still elevated and the epoxy resin cured at a higher temperature then ambient. The HMR drying time of five minutes was determined as the minimum drying time using the drying apparatus. A few laminates showed small wet spots on the surface. Table 4 indicates the number of laminates with an incompletely dried surface depending on the treatment combination. In recapitulation, each treatment combination was replicated seven times.

Table 4. Number of Laminates with an Incompletely Dried Surface

HMR Drying Time	HMR Spread Rate	HMR Solids Content	Number of Laminates
5 minutes	146 g/m²	10 %	3
5 minutes	220 g/m²	10 %	1

As mentioned above, the HMR drying temperature increased with increasing HMR drying time. Figure 9 shows a typical temperature curve of a drying HMR-treated surface. In Figure 9, a laminate having assigned a treatment combination with a HMR spread rate of 220 g/m², a HMR solids content of 5 % and a HMR drying time of 20 minutes was dried. Before drying, the surface temperature of the board was 25°C (arrow in Figure 9). Immediately after HMR application and placing the HMR-treated laminate beneath the IR lamps, the temperature increased constantly. The HMR drying temperature was not the same for each of the drying times. A shorter HMR drying time had a lower drying temperature, whereas a longer HMR drying time resulted in a higher drying temperature.

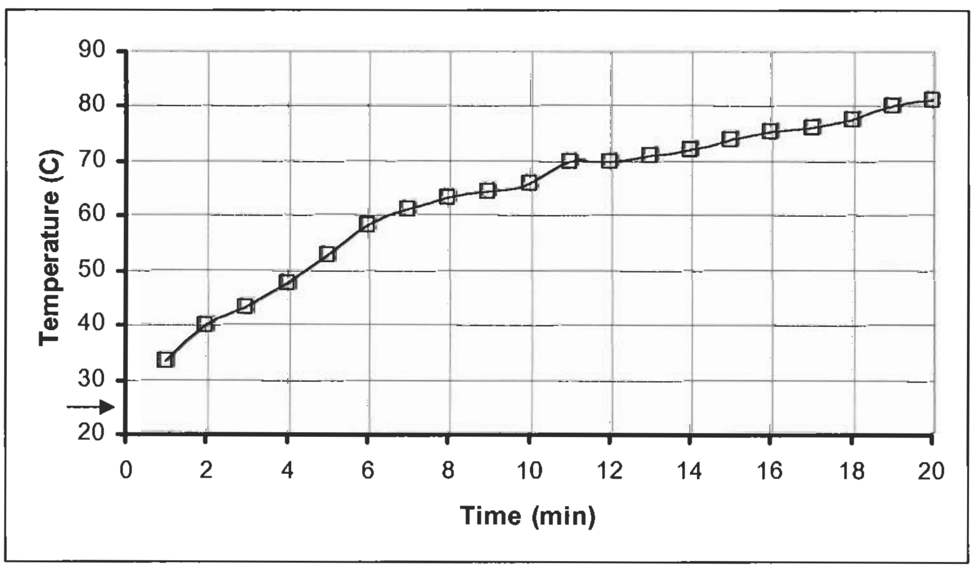

Figure 9. HMR Drying Temperature

The shear strength and percentage of wood failure measured on the shear blocks of each laminate are shown in the Appendix Tables B25 and B26. The mean of the three shear blocks was determined and is shown in Appendix Table B24. These means were used for the analysis of variance (ANOVA) provided by SAS®. The SAS File is shown in Appendix Table A1. In Appendix Table A1, the "INPUT" statement read in the variables T (=HMR drying time), S (=HMR spread rate), C (=HMR solids content), SHE_D (=shear strength dry in lbs/in^2), SHE_W (=shear strength wet in lbs/in^2), WF_D (=wood failure dry in %), and WF_W (=wood failure wet in %). The statements

SHEAR_D=SHE_D*0.0068948

SHEAR_W=SHE_W*0.0068948

converted the shear strength values from lbs/in^2 to MPa. The SAS statement "CARDS" listed all factorial treatment combinations and the four response variables. The SAS statement "PROC MEANS.....HMR1" provided the means, variances, standard deviations and COV's for each response variable. The SAS block statement "PROC GLM DATA=HMR1" calculated the ANOVA, the contrasts and interactions between treatment groups, and calculated the predicted values and the residuals of the linear additive model. Additionally, Duncan's Multiple Range Test was used as mean comparison method. The SAS block statement "PROC UNIVARIATE PLOT NORMAL" provided the test for normality of the residuals. The last SAS block statement "PRO GLM" carried out Levine's test for equality of variances calculated on the absolute values of the residuals. Appendix Table A2 lists all 140 observations.

Two response variables (shear strength dry and wood failure dry) showed non-normality of the residuals in the Shapiro-Wilk Test (Appendix Tables A4 and A8). The P-values (P<W) were below the 0.05 mark. Whereas, the variables shear strength wet and wood failure wet showed normal distributed residuals (Appendix Tables A6 and A10). The boxplots on all variables showed outliers within a range of 1.5 to 3.0 times of the inner-quartile range (Appendix Tables A5, A7, A9, and A11). The Levine's test showed inequality of variances for all four response variables. The Type III SS-Mode showed P-values below the 0.05 mark for at least one of the three factorial factors (T, S, and C). For all response variables the HMR drying time (T) had the strongest impact to inequality (Appendix Tables A12-A15). Table 5 shows the results of the Shiparo-Wilk Test (normality) and the Levine's Test (equality) at $\alpha = 0.05$.

Table 5. Normality and Equality of Variances of the Response Variables

Response Variable	Normality of Residuals	Equality of Variances
Dry Shear Strength	NO	NO
Wet Shear Strength	YES	NO
Dry Wood Failure	NO	NO
Wet Wood Failure	YES	NO

The inequality of variances can be seen in the variances of the treatment groups, too. Appendix Table A3 lists the variances of all twenty treatment groups for all four response variables. It can be seen that the variances cover a wide range of values. For example, the response variable shear strength dry had the biggest variance of 20.66 MPa^2 at the treatment combination T=1 (HMR drying time: 5 min), S=2 (HMR spread rate: 146 g/m^2), and C=10 (HMR solids content: 10 %). The smallest variance of 1.15 MPa^2 was

determined at the treatment combination T=4 (20 min), S=2 (220 g/m²), and C=10 (10 %). This means that the biggest variance was almost eighteen times as big as the smallest variance. The same pattern of inequality was seen for the other response variables, too. Table 6 summarizes the range of variances for all response variables.

Table 6. Variance Range for the Response Variables

Response Variable	Variance	
	Biggest Value	Smallest Value
Dry Shear Strength	20.66 MPa^2	1.15 MPa^2
Wet Shear Strength	7.01 MPa^2	0.37 MPa^2
Dry Wood Failure	610 $\%^2$	46 $\%^2$
Wet Wood Failure	1492 $\%^2$	39 $\%^2$

To eliminate non-normality and inequality the datasets were transformed. The response variables shear strength dry and wet were transformed to logarithms of the base 10. The response variables wood failure dry and wet showed according to Appendix Table A3 a smaller variance on each corner of the datasets, and a bigger variance at the center of the datasets. This means the wood failure in the ranges of 0-20 % and 80-100 % had lower variances then the wood failure between 20 and 80 %. Little and Hills (1978) suggest for this case the ARCSINE or angular transformation. Vick (1995) and Vick *et al.* (1995) applied the same transformation to their data. A 2nd SAS file was created. After transforming of the datasets, the results were similar to those explained previously. Only the response variable wood failure dry showed a normal distribution of the residuals (homogeneity) and equality of variances. Therefore, a 3rd SAS file was created containing transformed datasets, but a few observations were dropped from three out of four datasets. This SAS file is shown in Table Appendix B1.

The statements

```
LOGSH_D=LOG10(SHE_D*0.0068948)

LOGSH_W=LOG10(10+SHE_W*0.0068948)

ARWF_D=ARSIN(SQRT(WF_D/100))

ARWF_W=ARSIN(SQRT(WF_W/100))
```

created four new variables that were transformed to either the logarithm scale, or to the arcsine-square root scale. Before transforming, the logarithmic value of the shear strength wet was shifted by 10 MPa-units to the upper side of the logarithmic scale. This made sure that both shear strength variables were projected to the same section of the logarithmic scale. In the datasets, dropped observations were replaced by periods [.] as required by SAS®. The SAS file having transformed datasets with dropped data points is shown in Appendix Table B1. Appendix Table B2 shows a list of all observations.

The dropping of observations was based on the residuals and their distance from the center. The center, or average, of the residuals of each variable has the value of zero in a linear additive model. It was decided to eliminate observations having the biggest impact on the model. Outliers impact the linear additive model due to their deviation from the null-point of the boxplot. Therefore, the observations having the largest deviation to both sides of the center of the boxplot were dropped. The dropping of observations narrows the natural variation of the dataset and should be avoided. For this reason, if necessary, only two observations were dropped per dataset. No dropping was necessary on the variable percentage of wood failure under dry test conditions. All other variables had two dropped observations (Appendix Table B4). For this reason, the reader should keep in mind that all results (ANOVA, DMRT, etc.) are biased to a certain extent.

However, the circumstance that only two out of 140 observations were dropped from some of the response variables kept this bias in a low range.

The four response variables showed normally distributed residuals in the Shapiro-Wilk Test (Appendix Tables B12, B14, B16, and B18). The P-values (P<W) were above the 0.05 mark. The boxplots on the variables shear strength dry (Appendix Table B13) and shear strength wet (Appendix Table B15) showed outliers within a range of 1.5 to 3.0 times of the inner-quartile range. All others showed no outliers because of data transformation and data dropping (Appendix Tables B17 and B19). The Levine's test showed equality of variances for the variables shear strength dry (Appendix Table B20) and wood failure dry (Appendix Table B22). The Type III SS-Mode showed P-values above the 0.05 mark for all the three factorial factors (T, S, and C). The Levine's test showed inequality of variances for the variables shear strength wet (Appendix Table B21) and wood failure wet (Appendix Table B23). The Type III SS-Mode showed P-values below the 0.05 mark for at least one of the three factorial factors (T, S, and C). Table 7 shows the results of the Shapiro-Wilk Test (normality) and the Levine's Test (equality) on transformed datasets. Both tests were based on $\alpha = 0.05$.

Table 7. Normality and Equality of Variances of the Response Variables (Transformed Datasets with Dropped Data Points)

Response Variable	Normality of Residuals	Equality of Variances
Dry Shear Strength (LOG10)	YES	YES
Wet Shear Strength (LOG10)	YES	NO
Dry Wood Failure (ARSIN(SQRT))	YES	YES
Wet Wood Failure (ARSIN(SQRT))	YES	NO

The evidence of not meeting the assumptions of homogeneity and equality of variances didn't allow to analyze the response variables shear strength and percentage of wood failure for the water-soaked conditions using the ANOVA or other parametric statistics. However, homogeneity and equality of variances allowed to analyze the response variables of shear strength and percentage of wood failure for the dry conditions.

The ANOVA on the variable shear strength dry showed the following results. At α=0.05, the Type III SS-Mode indicated no significant differences between the main factors of the factorial (Table B4). However, the treatment separation using contrast coefficients showed a significant difference between the shortest HMR drying time of 5 minutes (T=1) compared to all other lamp drying times such as 10, 15 and 20 minutes (T=2, 3, and 4). This was confirmed by Duncan's multiple range test (Appendix Table B5). No significant differences were found in all interactions. The DMRT showed no significant differences between HMR spread rates (Appendix Table B6) and between HMR solids contents (Appendix Table B7). Table 8 shows the results of the single degree of freedom F-tests for factor A using contrast coefficients.

Table 8. ANOVA Contrasts of the Variable Shear Strength Dry

Contrast	F-Value	P-Value
24 hours vs. IR-heat Drying	0.18	0.67
5 min vs. 10-to-20 min	7.97	0.006**
10 min vs. 15 + 20 min	0.08	0.78
15 min vs. 20 min	0.02	0.88

Table 9 shows the results of the DMRT. The means of the shear strength for each group were derived from the LOG10-transformed dataset containing two dropped data points in the group for the 5-minutes HMR drying time.

Table 9. DMRT on the Variable Shear Strength Dry

Drying Time	Shear Strength Mean (MPa)	Number of Samples	Duncan Grouping
20 minutes	19.95	28	A
15 minutes	19.87	28	A
10 minutes	19.78	28	A
24 hours	19.73	28	A
5 minutes	18.58	26	B

The ANOVA on the variable wood failure dry provided the following results. At α=0.05, the Type III SS-Mode indicated a significant differences between the levels of the HMR drying time (T). A P-value of 0.0001 (F-values of 7.88 in the ANOVA table and 28.56 in the contrasts) indicated this (Appendix Table B8). The treatment separation using contrast coefficients showed a significant difference between the shortest HMR drying time of 5 minutes (T=1) compared to all other lamp drying times such as 10, 15 and 20 minutes (T=2, 3, and 4). This was confirmed by Duncan's multiple range test (Appendix Table B9). No significant differences were found in all interactions. The DMRT showed no significant differences between HMR spread rates (Appendix Table B10) and between HMR solids contents (Appendix Table B11). Table 10 summarizes the results of the single degree of freedom F-tests for factor A using contrast coefficients.

Table 10. ANOVA Contrast of the Variable Wood Failure Dry

Contrast	F-Value	P-Value
24 hours vs. IR-heat Drying	0.02	0.90
5 min vs. 10-to-20 min	28.56	0.0001**
10 min vs. 15 + 20 min	1.59	0.21
15 min vs. 20 min	1.36	0.25

Table 11 shows the results of the DMRT. The means of the percentage of wood failure for each group were derived from the ARSIN-square root-transformed dataset containing two dropped data points in the group for the 5-minutes HMR drying time.

Table 11. DMRT on the Variable Wood Failure Dry

Drying Time	Wood Failure Mean (%)	Number of Samples	Duncan Grouping
20 minutes	92	28	A
15 minutes	88	28	A
10 minutes	86	28	A
24 hours	85	28	A
5 minutes	68	26	B

Interaction charts were used to interpret the ANOVA results more precisely. All interaction charts (Figures 10-14) are based on the non-transformed and complete datasets. On the variable shear strength dry, the lowest shear strength was achieved at the shortest HMR drying time (5 minutes). The shear strength of about 18 MPa was significantly lower then all other levels of HMR drying time (Figure 10). As mentioned above, only the 5 minutes-HMR drying time is significantly different from all other HMR drying times. Figure 10 shows this circumstance clearly. It also shows clearly the ANOVA's difficulties to detect significant interactions. For example, the shear strength of samples with a HMR spread rate of 220 g/m^2 and a HMR solids content of 5 % doesn't follow a linear trend, whereas the same HMR spread but with higher solids content (10

%) is more bow-shaped. In general, the ANOVA is very precise when a high number of replications are used (Murphy and Myors 1998), but this is not the case here.

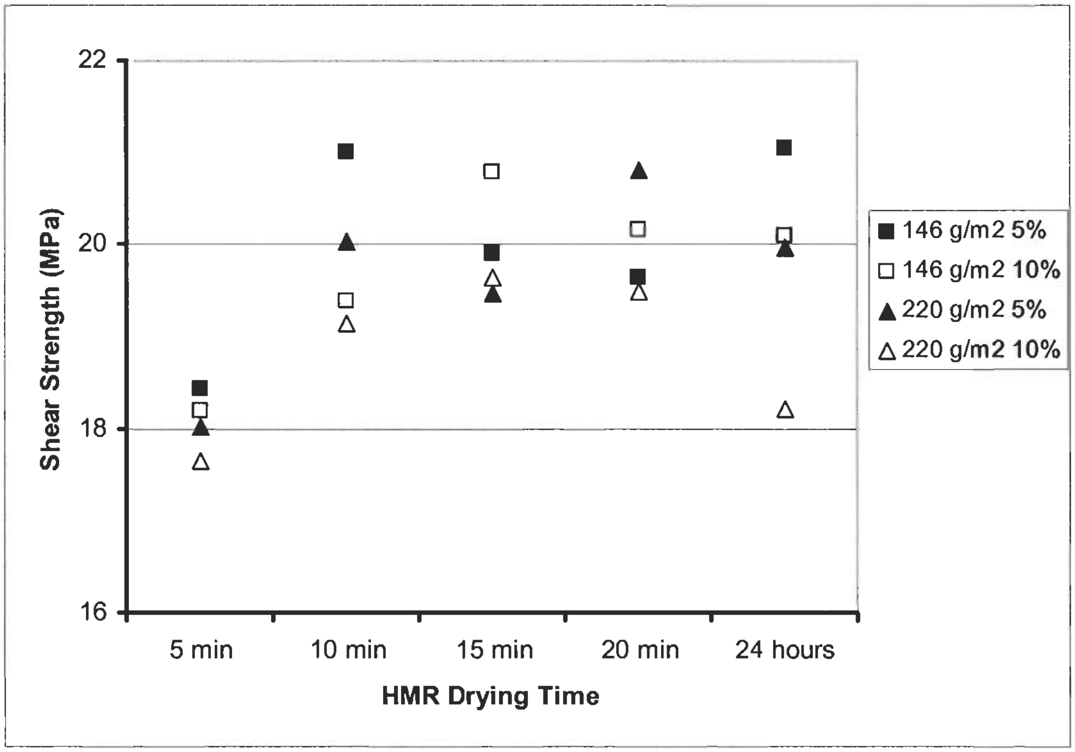

Figure 10. Interaction Chart of the Variable Shear Strength Dry

A similar situation was observed on the variable wood failure dry (Figure 11). The lowest wood failure was achieved with the shortest HMR drying time (5 minutes). Also, the values of wood failure do not follow a linear trend, but a general trend can be seen. By increasing the drying time, the wood failure increases in the same matter as the shear strength as discussed above. In both interaction charts it is obvious that a change in both the HMR spread rate and HMR solids content did not impact the response variable. Neither the shear strength dry (Figure 10), nor the wood failure (Figure 11) was impacted to a large degree.

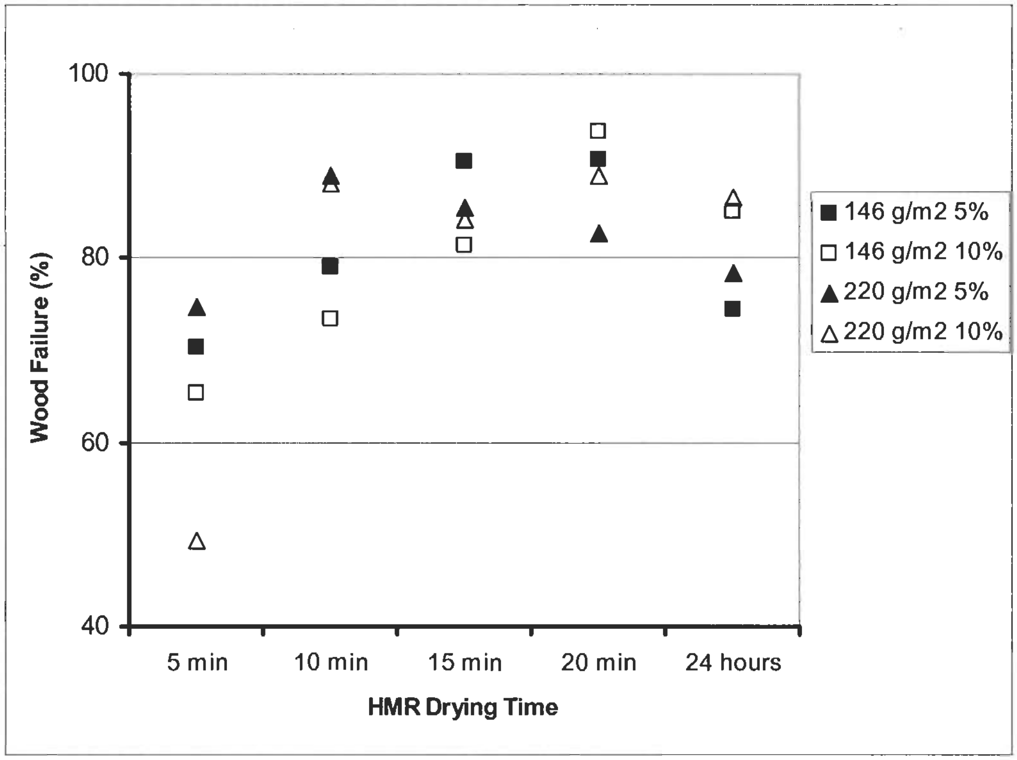

Figure 11. Interaction Chart of the Variable Wood Failure Dry

The interaction charts of the other two variables can be used for drawing conclusions even if the assumptions of parametric statistics were not met. For the response variable shear strength wet in Figure 12, it is obvious that there is a significant treatment effect. Under wet test conditions, the shear strength was affected to a greater extent by the HMR drying time then under dry test conditions. However, Chew (1976) and Jones (1984) state that each treatment has an effect, but sometimes, the ANOVA doesn't detect these treatment effects. In this case, both non-normal distributed residuals and inequality of the grouping variances were responsible for this. At the lowest level of the HMR drying time (5 min, T=1), the shear strength was the lowest. The shear strength of 4 MPa is below the 6 MPa-minimum level for structural adhesives. Increasing the HMR drying time to 15 minutes (T=3) the shear strength reached the maximum value of

9 MPa. Furthermore, in Figure 12 it can be seen that laminates dried at standard conditions (24 hours, T=5) didn't meet the minimum level for structural adhesives. Here, the shear strength varied from 4.5-7 MPa, which is a safety concern.

Epoxy resin cured at ambient conditions is likely to develop low strength (Pocius 1997, Bosch 1996, Bhatnagar 1996, Nakamura and Arima 1996). Ambient cured epoxy resins remain in a non-fully-cured status. In addition, the glass transition temperature (T_g) of epoxies remain low. Post-curing can elevate the T_g and can increase the bonding strength (Pocius 1997). Therefore, post-curing is common practice for wood-to-wood bondings using epoxy resin (Vick *et al.* 1998, Vick and Okkonen 1997, Vick *et al.* 1995). Something else has to be kept in mind. Water soaking is a very severe treatment. From Appendix Tables B25 and B26 it can be seen that the tangential length of the shear area (width) increased by about 8 % after water soaking. The bondline is under stress as a result of swelling. On ambient cured samples, such as the laminates cured at standard conditions (23±2°C and 65% relative humidity), epoxy resin bonds might fail under swelling stresses. However, laminates that were dried under IR lamps never cooled down during the bonding step. It is very likely that the epoxy resin had a shortened gel time and the curing process took place faster compared to laminates cured at standard conditions. The resin seemed to be more cross-linked. This explains the better strength performance of the IR-dried laminates.

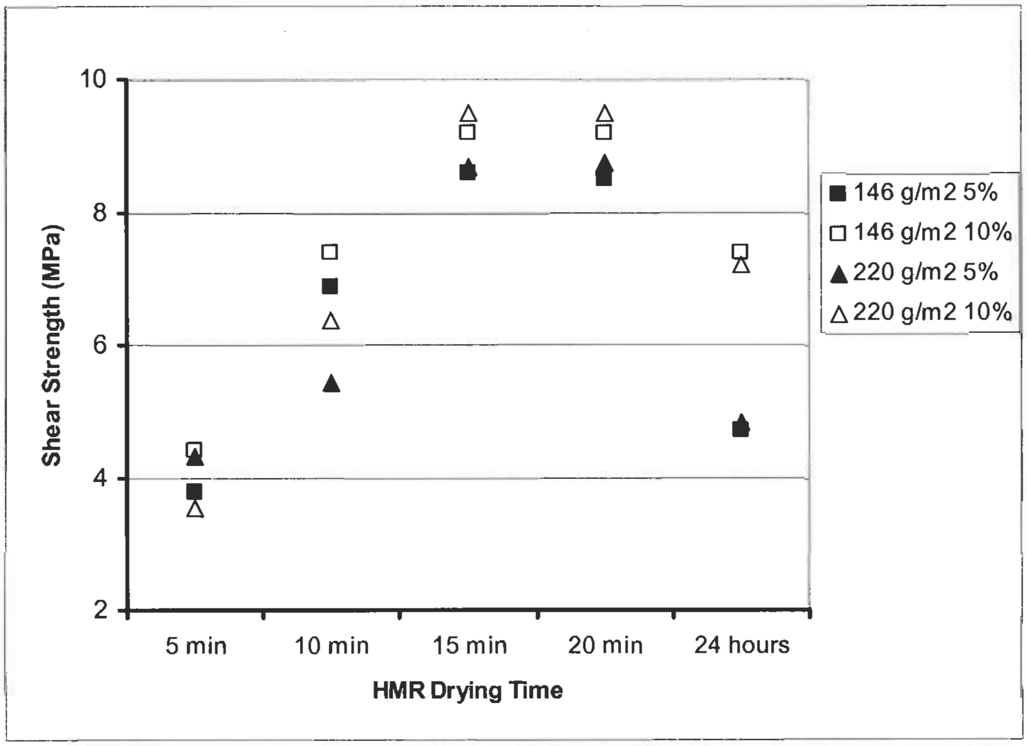

Figure 12. Interaction Chart of the Variable Shear Strength Wet

The same performance pattern took place for the response variable percentage of wood failure tested under wet conditions. Here the wood failure also increased with increasing HMR drying time, followed by a drop of wood failure on laminates cured at ambient conditions (Figure 13). The reason for not meeting the assumptions of parametric statistics could be caused by the small number of replications used in this experiment. Seven replicates per treatment combination might not be enough for providing an unbiased estimate of a true variance. Murphy and Myors (1998) quote that the ANOVA is very sensitive on detecting treatment effects when a high number of replications are used. Increasing the sample size can eliminate non-normal distributed residuals and inequality of the variances of the treatment groups.

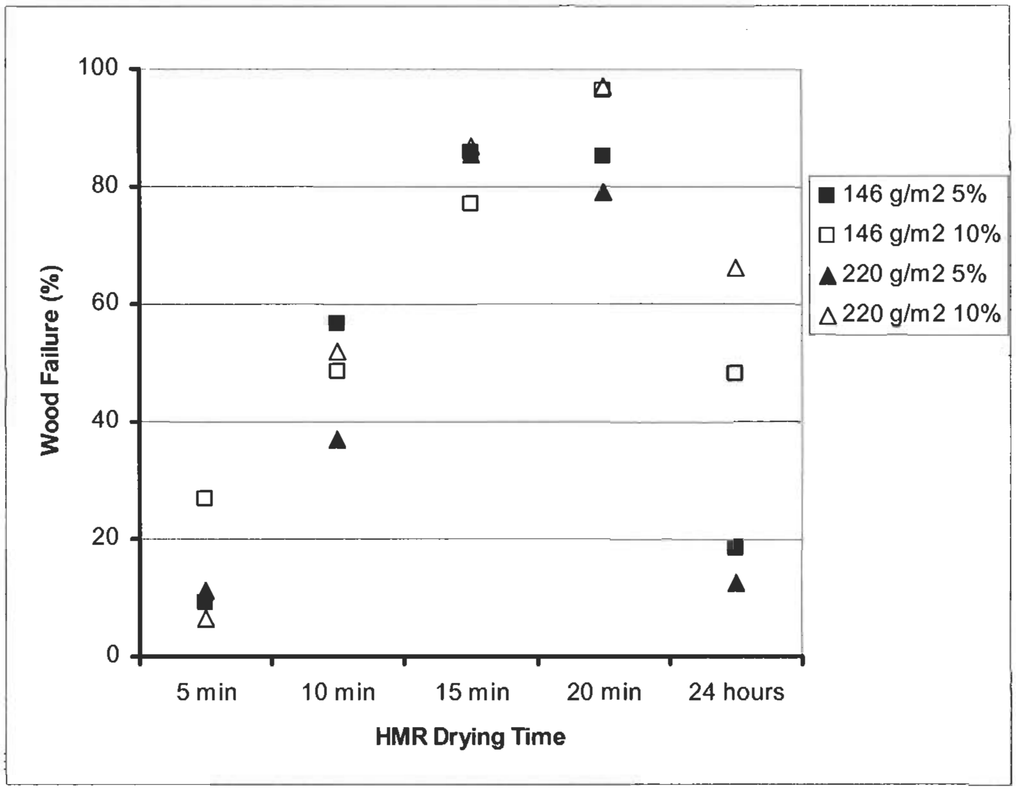

Figure 13. Interaction Chart of the Variable Wood Failure Wet

After carrying out this experiment and looking at the response of each variable at the two test conditions, power analysis can be used for determination of the required sample size per treatment. The sensitivity in detecting real differences between groups is called the power of a test 1-β (Maxwell and Delaney 1990). The first step in power analysis is to choose appropriate power levels α and 1-β for the experiment. α is usually used at 0.05. The power of the test should be somewhere between 0.80 and 0.95. The next step is calculating the effect size of a treatment as following.

Equation 4. Effect Size of a Treatment

$$d = \frac{\mu_{\max} - \mu_{\min}}{\sigma_{\varepsilon}}$$

d	effect size of a treatment
μ_{max}	largest population mean
μ_{min}	smallest population mean
σ_{ϵ}	standard deviation

From Figure 12 and Appendix Table A3 the following values were used to calculate the effect size (Equation 4) for the variable shear strength under wet conditions.

Maximum shear strength μ_{max} = 8 MPa

Minimum shear strength μ_{min} = 4 MPa

Average standard deviation σ_{ϵ} = 3 MPa

The effect size would be

$$d = \frac{8-4}{3} = 1.333$$

From Table 3.7 in Maxwell and Delaney (1990) the minimum sample size would be somewhere around fifteen samples needed per group at α=0.05 and at a power 1-β=0.80. This means this experiment would need twice the number of replications then it was originally designed for. Another explanation for not meeting the assumptions of

parametric statistics could be a natural difference of the variance between groups (Little and Hills 1978). In general, some treatment groups can have a bigger variance then others.

2.5. Conclusions and Recommendations

The conclusions of this experiment are as follows.

1. The HMR drying time affected the response variables shear strength and percentage of wood failure to the greatest extent. The drying apparatus showed the lowest bond performance at a HMR drying time of 5 minutes. This drying time is too short and results in unacceptable adhesive bond strength. At a HMR drying time of 10 minutes, the bonding performance reached the same level as for laminates bonded under standard conditions (23±2°C and 65 % RH). The best bonding performance was measured at a HMR drying time between 15-20 minutes. Both test conditions showed a high shear strength combined with a high percentage of wood failure.
2. The HMR spread rate didn't significantly impact the bond properties. Because of the higher amount of water within the HMR solution, I recommend to use the lower spread rate of 146 g/m^2. Less water applied to the wood surface leads into less heat required to dry the HMR solution. In addition, the moisture change in the upper parts of the wood laminate is not so severe for a low HMR spread rate then for a high spread rate. It has to be kept in mind that the entire amount of water in the HMR solution does not evaporate from the wood surface. Some portion of the

water penetrates into the wood and is forced into the core of the wood laminate due to IR-heat radiation. The elevated moisture content will compensate its distribution over time, but during the bonding process a pre-stressed bondline might be created. The pre-stressing effect is larger for a larger moisture change.

3. The HMR solids content didn't impact the bond performance either. There was no significant interaction measured. To keep the costs of HMR low I recommend to use a HMR solids content of 5 %. The HMR drying experiment showed that the entire HMR-drying process is only sensitive to the HMR drying time. It is not sensitive to minor changes in spread rate and solids content. This means minor changes don't impact the bond performance. This is very convenient for the industrial application of HMR too. The set-up of a production line as shown in Figure 1 has a certain degree of freedom. This freedom allows small deviations in spread rate and solids content without causing a loss in the bonding quality.
4. The circumstance of bonding the laminates in a more or less "hot" stage increased the bond performance. This means that post-curing of the epoxy adhesive as used in previous research might not be necessary anymore. The use of a similar industrial drying station could replace the expense of post-curing in autoclaves. It might be possible to shorten the HMR drying time using either stronger IR-heat lamps or by placing the wood laminates at a closer distance to the heat source. In my opinion, the drying temperature should not be too high. If the surface temperature is kept too high, a strong lateral moisture movement within the wood laminate will take place resulting in the creation of a pre-stressed bondline. This

should be avoided. I recommend a longer drying time (10-15 minutes) as used in this experiment in combination with a drying temperature between 60-75°C.

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Chapter 3

REINFORCING STRUCTURAL WOOD MEMBERS USING SEEMANN'S RESIN INFUSION MOLDING PROCESS

3.1. Introduction

In 1990, Bill Seemann invented the Seemann composites resin infusion molding process (SCRIMP™). The 1st of 10 U.S. patents owned by TPI Composites, Inc., Warren, RI, was issued on February 20, 1990 and the latest was issued on December 12, 2000. In the basic SCRIMP™ process, fiber reinforcements, core materials and various inserts are laid up in a tool while dry, followed by a vacuum bag that is placed over the lay-up and sealed to the tool. The part is then placed under vacuum and the resin is introduced into the part via a resin inlet port and distributed through the laminate via a flow medium and a series of channels, saturating the part. The vacuum pressure compacts or debulks the dry fibers. For this reason, parts made with the SCRIMP™ process have high fiber volumes, typically about 60-75 % fiber by weight, depending on the type of fiber, the fiber architecture and the type of resin used. The vacuum removes all of the air from the lay-up before and while resin is introduced. The pressure differential between atmosphere and the vacuum provides the driving force for infusing the resin into the lay-up (from the website http://www.jboats.com). TPI Composites, Inc., is using the SCRIMP™ process for the manufacture of all their series of boats.

For FRP-wood composites, Lopez-Anido *et al.* (2000), Lopez-Anido *et al.* (2002a), and Lopez-Anido *et al.* (2002b) carried out performance experiments on structural-glued-laminated timber (glulam) with fiber-reinforced polymer (FRP) composite reinforcement for structural applications. The tested FRP-wood composite contained two reinforcements using the SCRIMP™ process. Vinyl ester resin was used as the matrix and E-glass fabrics and carbon fibers were used as reinforcements. Herzog *et al.* (2003) tested the same FRP-wood composites in terms of resistance against delamination after preservative treatment. All tests presented by these researchers showed a good performance of SCRIMP™ reinforcements.

This chapter contains two main parts. First, it explains in detail the procedure to use Seemann's resin infusion-molding process (SCRIMP™) to manufacture wood-FRP glulams and laminates. Lopez-Anido *et al.* (2000), Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b) and Herzog *et al.* (2003) used the following stacking sequence for the SCRIMP™-FRP layer. The first layer of the FRP-laminate was a single layer of a chop-strand mat (CSM) that provides randomly orientated fibers embedded in a resin matrix. This CSM-layer transfers the loading stresses from the FRP-layer to the wood member and is therefore the layer that is located closest to the wood-resin interphase (Daniel and Ishai 1994). Following the CSM-layer, numerous layers of unidirectional fabrics are added and those are responsible for the load bearing. The resin-fiber volume ratio differs between the CSM and unidirectional fabrics. The CSM layer has a lower fiber-resin volume ratio than the unidirectional layers (Daniel and Ishai 1994). In this thesis, the stacking sequence contained one CSM-layer and thirty layers of VEW260 unidirectional woven fabrics giving a total FRP-thickness of approximately 19 mm.

The 2^{nd} objective is to present results on the bond quality of SCRIMP™ reinforced wood composites. In this part, the results of Chapter 2, the accelerated drying of HMR, was applied to improve the reinforcement process and to reduce the total production time. The results of the bond quality presented here will be published by Herzog *et al.* (2003). The results presented here focus only on untreated control samples, whereas Herzog *et al.* (2003) gives a general overview.

To evaluate the bonding performance, two ASTM tests were applied. The determination of the shear strength and the percentage of wood failure in compression were carried out according to ASTM D 905 (1994). Again, this test is quick and reliable. It is used mainly for screening tests such as presented in Lopez-Anido *et al.* (2000), Lopez-Anido *et al.* (2002a), and Lopez-Anido *et al.* (2002b). The 2^{nd} test to evaluate the bonding performance is ASTM D 2559 (1998), and it determines the delamination after exposure to cycles of water-soaking, drying and steaming and simulates the exterior exposure during the lifetime of a structural member. The previous mentioned authors used the same tests to screen the most appropriate FRP-wood composites. The results presented are based on novolak- based HMR.

3.2. Materials and Testing Equipment

3.2.1. n-HMR Coupling Agent

For this chapter, the novolak-based HMR coupling agent was used. The HMR solids content was 5 % and the mixing procedure as described in Chapter 2.2.1 was used.

After adding the final amount of formaldehyde solution, the pH was determined. The pH was adjusted by adding 3-molar sodium hydroxide solution to the HMR solution. The pH was held in a range between 8.5 and 9.0. This solution was allowed to react for one hour. Within the next one hour the n-HMR solution was applied to wood. Table 12 shows the ingredients of the HMR solution.

Table 12. Ingredients of n-HMR

Ingredients	Amount of Chemical (g)
Crystalline Resorcinol	3.34
Deionized Water	90.43
3-Molar Sodium Hydroxide Solution	2.44
Formaldehyde Solution (37.1% Formalin)	
For Novolak Stage	0.95
For Final Activation Stage	2.84
Dodecyl Sulfate Sodium Salt	0.50

3.2.2. Wood Species and Wood Samples

The tests were conducted on southern yellow pine (*Pinus spp.*)

3.2.2.1. Wood Boards

Sample boards were cut from flat-sawn lumber having dimensions of 2000 x 125 x 19 mm (length x width x thickness). The lumber was stored at standard conditions (23±2°C and 65 % RH) for at least eight weeks.

3.2.2.2 Glulam Billets

To test the heat-accelerated durability (ASTM D 2559, 1998) FRP reinforced glulam billets were used. The manufacture of the glulam billets is described in detail in Hong (2003). However, a short overview of the billet manufacture is described as follows. Six laminate boards from flat-sawn southern yellow pine having the dimensions of 610 x 125 x 19 mm (length x width x thickness) were bonded in a lamination press. One hour before bonding, the boards were planed with 10 m/min planer feeding speed. PRF adhesive using a spread rate of 400 g/m² per bondline was used. The laminate boards were clamped with 690 kPa pressure for at least 24 hours. After clamping, the billets were stored at standard conditions (23±2°C and 65 % relative humidity) for at least four weeks. The ingredients of PRF resin are shown in Table 13. The mixing procedure was as follows. 9.6 g of catalyst were added to 18.4 g deionized water. The solution was stirred for 5 minutes. 72 g of PRF resin were added to the solution followed by stirring for 5 minutes.

Table 13. Ingredients of the PRF Resin

Ingredients	Amount of Chemical (g)
Liquid PRF Resin	72.0
Paraformaldehyde Catalyst	9.6
Deionized Water	18.4

Following PRF adhesive was used.

- Cascophen™ LT-5210J Liquid PRF resin from Borden Chemical, Inc., Columbus, OH

- Cascoset FM-6210 Paraformaldehyde catalyst from Borden Chemical, Inc., Columbus, OH

3.2.3. Vinyl Ester Resin

Experiments using the SCRIMP™ process were carried out with Derakane 411-C-50 resin. The following mixing procedure was used for all vinyl ester resins. From the supplier's container, the vinyl ester was poured into a PVC or PE container. The catalyst (2-butanone peroxide) was added to the resin in a mixing ratio between 1:100 and 1:50 by weight. This solution was stirred for 5 minutes. Immediately after stirring, the resin solution was applied. Depending on the room temperature, the gelling time of this solution was between 40-60 minutes.

The following chemicals are used for making vinyl ester resin.

- Derakane epoxy vinyl ester resin 411-C-50, containing styrene monomer, from The Dow Chemical Company, Midland, MI.
- 2-Butanone peroxide, ~32 wt% solution in phthalate-free plasticizer mixture (Lupersol® DHD-9*) from Sigma-Aldrich Inc., Milwaukee, WI.

3.2.4. SCRIMP™ Equipment and FRP Materials

For the SCRIMP™ process, the following materials and chemicals were used.

- E-glass VEW260 (26 ounces/yard^2 or 882 g/m^2) unidirectional woven fabric from Brunswick Technologies, St. Gobain.
- Chopped strand mat (CSM), from Brunswick Technologies, St. Gobain.
- Braid-reinforced PVC tubing, inner-diameter 9.5 mm, wall thickness 3.2 mm from McMaster-Carr, Dayton, NJ.
- Super 77, Spray Adhesive from 3M Adhesives Division, St. Paul, MN.
- Sealant Tape SM-5229 Gray from Northern Fiber Glass, Hampton, NH.
- Wrightlon® 5400 nylon bagging film from AIRTECH International, Inc., Huntington Beach, CA
- Flow medium
- Bleeder Lease® B Tightly woven, coated nylon peel ply from AIRTECH International, Inc., Huntington Beach, CA
- Metal wire (1 mm diameter)

3.2.5. INSTRON Testing Frame

The shear strength (ASTM D 905, 1994) was determined on an INSTRON testing frame (Figure 6, Chapter 2).

3.3. Methods

3.3.1. SCRIMP™ Reinforcement of a Wood Glulam

This chapter covers the reinforcement process of glulam billets. Glulam billets are usually used for the determination of the delamination according to ASTM D 2559 (1998). The dimensions of the glulam were 610 x 125 x 110 mm (length x width x height). Figure 14 shows a glulam reinforced with SCRIMP™.

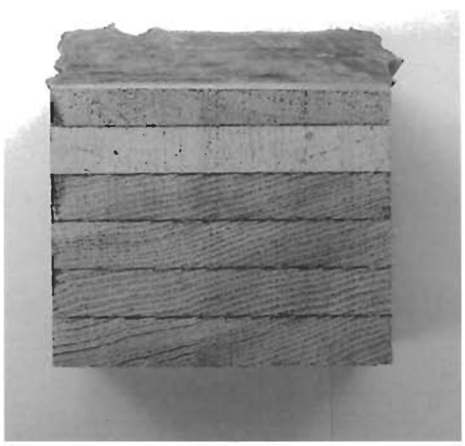

Figure 14. **Cross Section of a Reinforced Glulam Billet**

The reinforcement side of the wood glulam was planed prior to the application of the HMR coupling agent. A planer feeding speed of 10 m/min was used. Within the next 30 minutes, the n-HMR was applied to the glulam by brushing. The HMR solids content was 5 % and the HMR spread rate was 146 g/m². After drying the HMR treated glulam surface at standard conditions for 24 hours, the FRP layer was prepared. The composition

of an E-glass/vinyl ester resin reinforced glulam using the SCRIMP™ process is shown in Figures 15 and 16.

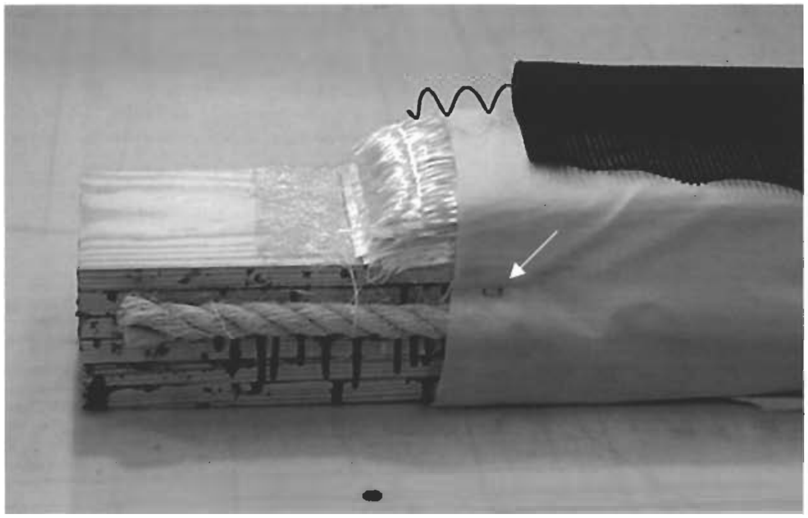

Figure 15. SCRIMP™ Components (a)

The HMR treated glulam side (A) was cleaned from potential dust using a brush. A sisal rope (B) was attached to the glulam side perpendicular to the reinforced side using Super 77 Spray Adhesive. The rope was aligned in a distance of about 10-20 mm from the top edge of the glulam. The total length of the rope was kept 20-30 mm shorter than the total length (610 mm) of the glulam. The FRP layer containing one layer of chop-strand mat (C) and thirty layers E-glass VEW260 unidirectional woven fabric (D) was laid up on the top side of the glulam. A total FRP-thickness of approximately 19 mm was used. Once the fabric layers were stacked, the top part of the glulam was covered with a peel ply layer (E). The peel ply was attached to the glulam using staples (arrow in Figure 15). The stacked fabrics were compressed slightly by stretching the peel ply downward. This prevented a sliding of the fabrics, and kept them compacted. The flow

medium (G) was fixed with Super 77 Spray Adhesive onto the top of the peel ply. The total area covered by the flow medium was smaller than the total size of the FRP-layer. Later during infusion, the resin was forced to flow through both the peel ply and the fabrics, before it reached the sisal rope. A metal coil (F) that was placed inside of the flow medium prevented the flow medium from collapsing caused by the vacuum. The metal coil was aligned along the longitudinal axis of the billet on the opposite side of the sisal rope. This insured that the infused resin penetrated along the entire FRP-layer, and the flow front was uniform along the longitudinal axis.

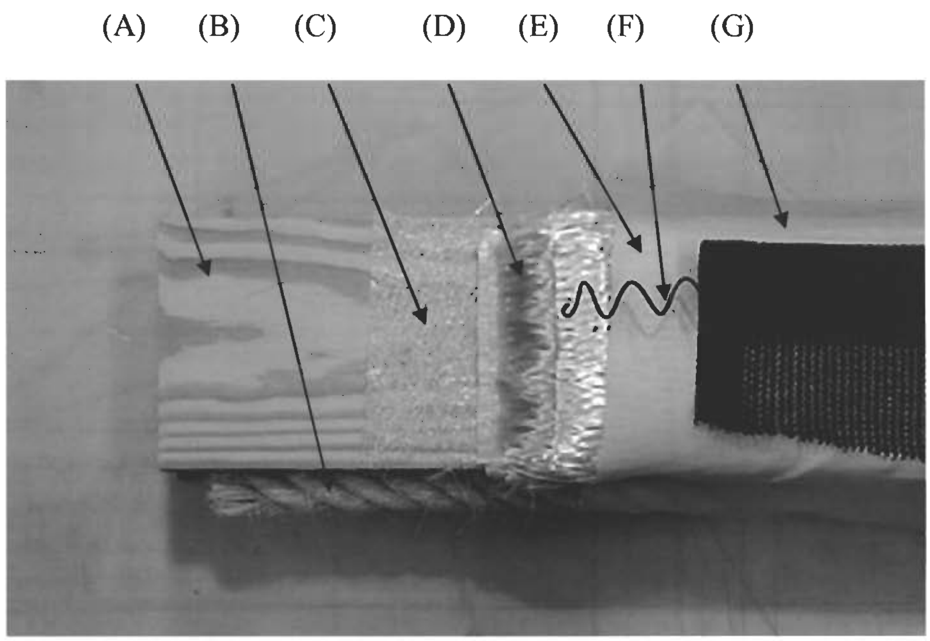

Figure 16. SCRIMP™ Components (b)

Both sharp ends of the metal coil were twisted backward (arrow in Figure 17) to prevent the vacuum bag from being punctured and causing leaks. The diameter of the metal was about 20 mm. The total length of the metal coil was kept the same as the total length of the flow medium.

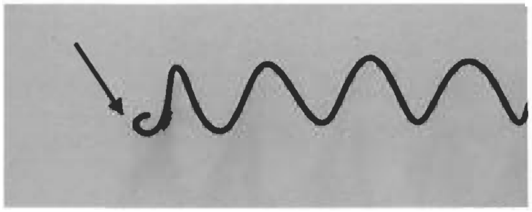

Figure 17. Metal Coil

Two 1200 mm long PVC tubes were sealed with sealant tape at a distance of approximately 100 mm from the tube end (Figure 18).

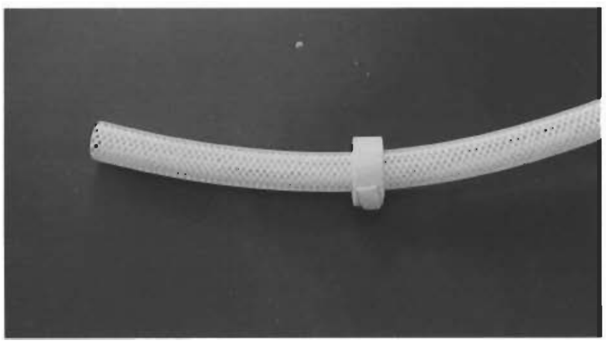

Figure 18. PVC Tube with Sealant Tape Belt

The glulam was placed in the vacuum bag. Figures 19 and 20 show the sealing and the position of the glulam within the sheet of the vacuum bag. A 1200 x 1200 mm sheet of vacuum bag was used for covering the glulam. The sheet was folded resulting in two half's of 600 x 1200 mm coverage area (arrows in Figure 19). The glulam was placed in the center of one half of the sheet such as that the longitudinal axis of the glulam was aligned parallel to the longer side of the folded vacuum bag. The sealant tape was attached onto the bag from one end of the folding edge to the other end of the folding edge surrounding the entire glulam. An appropriate sealing of the vacuum bag was

insured by crossings of the sealant tape at the two corners of the sealed area (arrow in Figure 20).

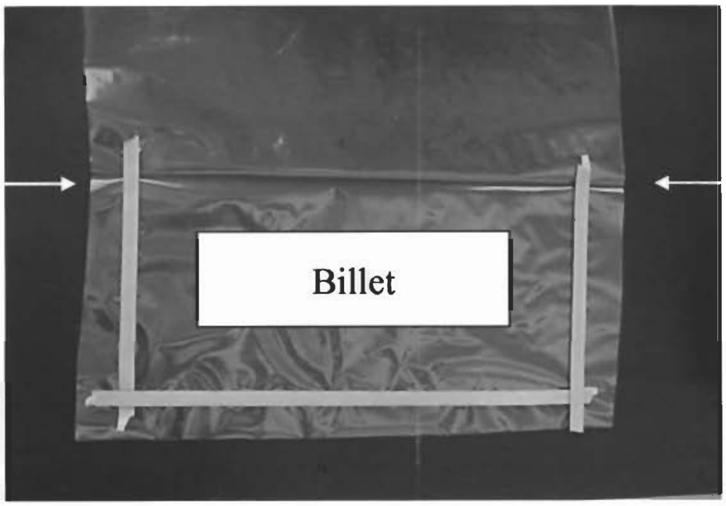

Figure 19. Billet Position within the Vacuum Bag

The tubes were attached onto the sealant tape at the positions shown in Figure 20. The tubes were attached this way so that one tube was on the glulam side with the sisal rope, whereas the other tube was on the metal coil side.

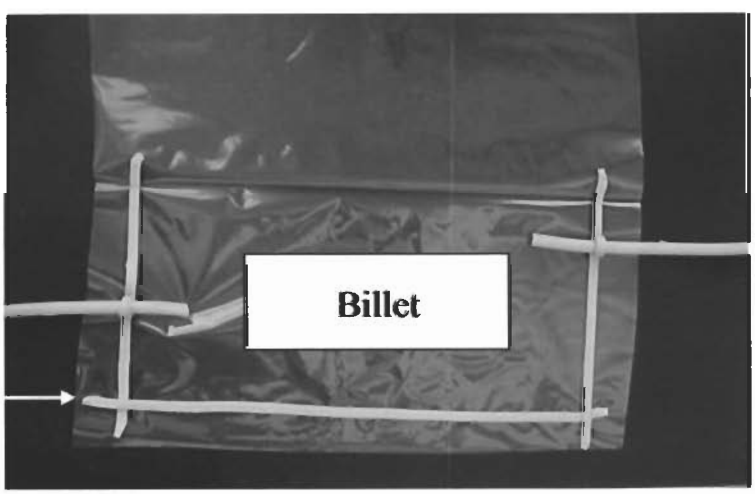

Figure 20. Positions of Vacuum and Resin Tube

The glulam was covered with the second half of the vacuum bag. The bag was sealed from one folding edge to the other folding edge. After completing the sealing of the vacuum bag, the tubes were connected to metal coil and sisal rope as shown schematically in Figure 21. The resin tube connected the flow medium, with the resin reservoir. The vacuum tube connected the sisal rope with the resin trap, which had the purpose of trapping the excess resin flow. Resin trap and vacuum pump are shown in Figure 22.

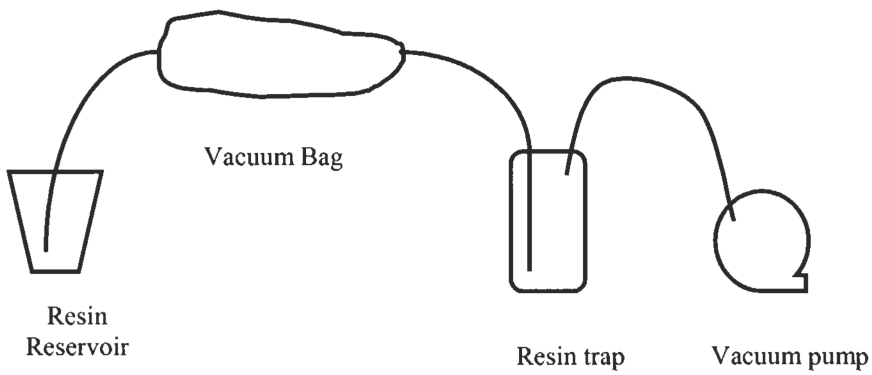

Figure 21. Schematic Function of SCRIMP™

The next step was to test the bag for appropriate sealing. The vacuum pump was adjusted at a vacuum level of 635 mm mercury. The resin tube was clamped and the bag was placed under vacuum. After clamping the vacuum tube, the vacuum was kept for 10 minutes and the bag was checked for any leaks. This procedure was repeated as long all leaks were sealed.

Figure 22. Resin Trap and Vacuum Pump

In a PVC container (resin reservoir, Figure 23), catalyst (2-Butane peroxide) was added to 2.5 kg vinyl ester resin in a weight ratio of 1:50. This solution was mixed for 5 minutes.

Figure 23. Resin Reservoir

After unclamping the resin tube, the bag was infused. The resin spread across the flow medium, and penetrated the fabric layers. The white color of the glass fabrics disappeared during the next 10-15 minutes. After about 20 minutes, the infusion was completed and the color of the FRP was dark-green (Figure 24). At that moment, the level of vacuum was reduced to 380 mm mercury. The lower level of vacuum was held for further 3-4 hours until the FRP layer was cured. A rise in the surface temperature

(45°C) indicated complete gelling of the vinyl ester within the bag. At that time, the vacuum was broken and the pump was shut off. Continued curing over night made sure that the FRP-layer developed its maximum strength properties. Figure 24 shows an infused part. Figure 25 shows the connections of the vacuum tube with the sisal rope. Figure 26 shows the connection of the resin tube with the metal coil respectively the flow medium. Figure 27 shows the tube-vacuum bag sealing.

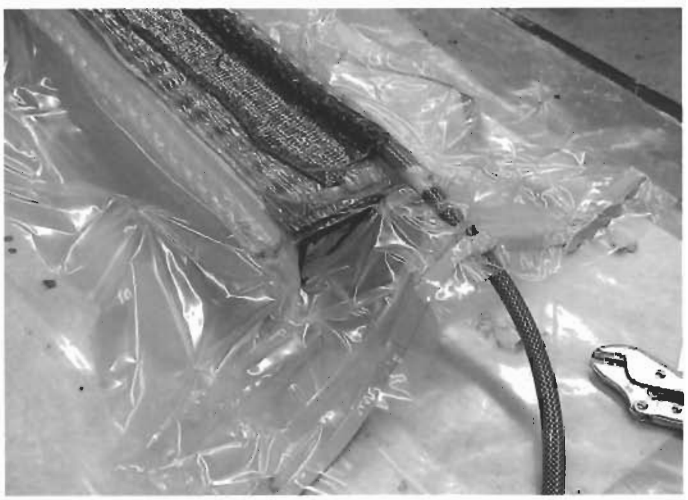

Figure 24. Infused Glulam Billet

Figure 25. Connection of the Vacuum Tube to the Sisal Rope

Figure 26. Connection of the Resin Tube to the Flow Medium

Figure 27. Sealing Connection of the Vacuum Tube

After curing over night, the vacuum bag was removed and the reinforced glulam was stored at standard conditions (23±2°C and 65 % RH) for at least one week.

3.3.2. SCRIMP™ Reinforcement of a Wood Board

For the determination of the shear strength and percentage of wood failure in compression according to ASTM D 905 (1994), wood-FRP laminates were used. To reinforce a laminate the same technique as described in Chapter 4.3.1 was used. The only

difference was that instead reinforcing a glulam billet a one-layer wood laminate was used. The dimensions of the wood laminate were 610 x 125 x 19 mm (length x width x thickness). The HMR solids content was 5 % and the HMR spread rate was 146 g/m². After curing of the FRP layer, the samples were stored at standard conditions (23±2°C and 65 % RH) for at least one week.

3.3.3. Shear Strength and Wood Failure of SCRIMP™ Reinforced Laminates

This experiment was part of an experiment carried out by Herzog *et al.* (2003). In this experiment, the effect of both oil-borne preservative systems and carriers of preservatives on the adhesive bondlines of FRP-glulam composite beams was investigated. Four types of wood-FRP laminates were exposed to five treatments. The FRP types were as following.

- Resin infused E-glass/vinyl ester using SCRIMP™
- Pultruded E-glass/urethane pre-consolidated sheets bonded with urethane adhesive
- Continuous laminated E-glass/epoxy pre-consolidated sheets bonded with epoxy adhesive
- Resin infused carbon/vinyl ester using SCRIMP™

The treatments were as following.

- Creosote (preservative 1)

- Copper naphthenate (preservative 2)
- Diesel (carrier 1)
- Mineral spirit (carrier 2)
- Untreated control

The experiment was designed as a split-plot treatment arrangement in completely random (Steel *et al.* 1997, Snedecor and Cochrane 1989, Little and Hills 1978). Each treatment was replicated four times. In this chapter, only the results of the untreated control samples are presented. Four boards of southern yellow pine having the dimensions of 610 x 125 x 19 mm (length x width x thickness) were reinforced using the SCRIMP™ process. The boards were planed using 10 m/min planer feeding speed. Within the next one hour, the boards were treated with n-HMR. The HMR spread rate was 146 g/m² and the HMR solids content was 5 %. After application of HMR, the boards were stored at standard conditions for 24 hours. After conditioning, the FRP layer was stacked. One layer of E-glass/CSM was used followed by thirty layers of E-glass VEW260 unidirectional woven fabrics. The total thickness of the FRP layer was approximately 19 mm. The laminates were vacuum infused using the SCRIMP™ process as described in Chapter 4.3.1 of this thesis. Vinyl ester resin and catalyst was used in a mixing ratio of 100:1 by weight. A total amount of 2.5 kg resin was used. After curing over night, the vacuum bag was removed and the wood-FRP laminate was stored at standard conditions for at least one week. After conditioning, twenty shear blocks were cut from each laminate. The cutting of the shear blocks was carried out in two steps. In the 1st step, the FRP layer was cut using a diamond circle blade. In the 2nd step, the wood

layer was cut on the table saw. For each treatment combination four shear blocks were randomly selected from each of the four laminates giving a total number of sixteen shear blocks. After assigning all treatment combinations, the shear blocks were treated in a treatment cylinder. The treatment process is described in Herzog *et al.* (2003). On eight shear blocks the shear strength and the percentage of wood failure were determined at standard conditions (23±2°C and 65 % RH) and on eight shear blocks the same was done for the water-soaked conditions (20 minutes soaking at 635 mm mercury vacuum followed by soaking under 520 kPa pressure for 20 minutes). The test was carried out according to ASTM D 905 (1994). The percentage of wood failure was estimated to the nearest 5 %. The mean of the shear strength and wood failure of the two shear blocks from each laminate was determined and used for the ANOVA. A single treatment combination provided four response variables described as follows.

- Bondline shear strength under standard conditions
- Bondline shear strength for the water-soaked condition
- Bondline wood failure percentage under standard conditions
- Bondline wood failure percentage for the water-soaked condition

3.3.4. Shear Strength and Wood Failure of Heat-Accelerated Dried SCRIMP™ Reinforced Laminates

This experiment was based on the results of Chapter 2 of this thesis. The aim of this experiment was to reduce the total production time of a reinforced laminate using the

SCRIMP™ process. Instead of drying the HMR-treated wood under standard conditions (23±2°C and 65 % relative humidity), the drying was done using the IR-drying apparatus described in Chapter 2. Chapter 2 showed only little differences among the three HMR factors (HMR drying time, HMR spread rate, HMR solids content). No factor had a significantly better performance then the others. Therefore, the following treatment combination was used.

HMR drying time: 15 minutes

HMR spread rate: 146 g/m²

HMR solids content: 5 %

Three laminates of southern yellow pine having the dimensions of 300 x 125 x 19 mm (length x width x thickness) were reinforced using the SCRIMP™ process. Beginning with the first laminate, the surface was planed using 10 m/min planer feeding speed. Within the next hour, the laminate was treated with n-HMR. The HMR spread rate was 146 g/m² and the HMR solids content was 5 %. Immediately after application of HMR, the laminate was dried under IR lamps using a HMR drying time of 15 minutes. Immediately after drying, the FRP layer was stacked. One layer of E-glass/CSM was used followed by thirty layers of E-glass VEW260 unidirectional woven fabrics. The laminate was vacuum infused using the SCRIMP™ process as described in Chapter 4.1 of this thesis. Vinyl ester resin and catalyst were used in a mixing ratio of 100:1 by weight. A total amount of 1.5 kg resin was used. After curing over night, the vacuum bag was removed and the wood-FRP laminate was stored at standard conditions for at least

two days. The manufacturing was continued until three laminates were produced. After conditioning, six shear blocks were cut from each laminate. The cutting of the shear blocks was carried out in two steps. In the 1st step, the FRP layer was cut using a diamond circle blade. In the 2nd step, the wood layer was cut on the table saw. The shear strength and the percentage of wood failure were determined at standard conditions (23±2ºC and 65 % RH) and for the water-soaked condition (20 minutes soaking at 635 mm mercury vacuum followed by soaking under 520 kPa pressure for 20 minutes). The percentage of wood failure was estimated to the nearest 5 %. A single treatment combination provided four response variables described as follows.

- Bondline shear strength under standard conditions
- Bondline shear strength for the water-soaked condition
- Bondline wood failure percentage under standard conditions
- Bondline wood failure percentage for the water-soaked condition

3.3.5. Testing of the Shear Strength and Wood Failure

The shear strength was determined using the INSTRON testing frame. The loading was in shear by compression (Figure 28) and the loading speed was 1.27 mm/min. The shear strength and percentage of wood failure was determined at two conditions. The shear strength at standard conditions was determined at 23±2ºC and 65 % RH, and the shear strength for the water-soaked conditions was determined after soaking in water under vacuum (635 mm mercury) for 20 minutes followed by soaking in water

under 520 kPa pressure for another 20 minutes. After determining the shear strength, the percentage of wood failure (patterned in Figure 28) in the bondline area was estimated to the nearest 5 %. Figure 28 shows on the left side the loading direction of a shear block, and on the right side the shear area (50 x 42 mm).

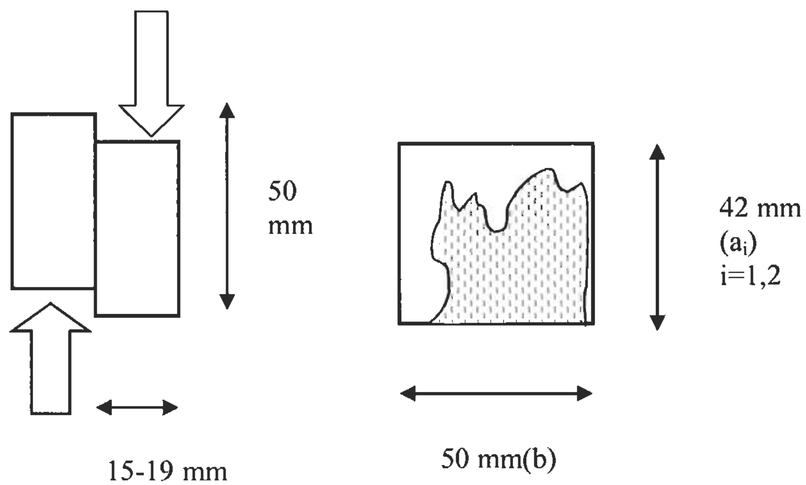

Figure 28. Shear Block Loading (Left Side) and Shear Area (Right Side)

The shear area was measured using a caliper. The shear strength was calculated using the following formula.

Equation 5. Calculation of the Shear Strength

$$P = \frac{F}{A}$$

P apparent shear strength (Pa)

F load to breakage (N)

A shear area (m^2)

The shear area was not exactly rectangular. Due to the natural inaccuracy of table saws, the shear area was more like a parallelogram. The length of the shear area in longitudinal direction (a_i in Figure 28) of the wood fibers was not the same on both sides. The length of the shear area in tangential direction (b) of the wood fibers was indeed the same on both sides. Therefore, the area was calculated using Equation 6.

Equation 6. Calculation of the Shear Area

$$A = \frac{a_1 + a_2}{2} \cdot b$$

a_1 length 1 of the shear area in longitudinal direction (m)

a_2 length 2 of the shear area in longitudinal direction (m)

b length of the shear area in tangential direction (m)

3.3.6. Delamination of SCRIMP™ Reinforced Glulams

This experiment was also part of an experiment carried out by Herzog *et al.* (2003). The effect of oil-borne preservative systems on the adhesive bondlines of FRP-glulam composite beams was investigated. Three types of wood-FRP laminates were exposed to five treatments. The FRP types were as following.

- Resin infused E-glass/vinyl ester using SCRIMP™
- Pultruded E-glass/urethane pre-consolidated sheets bonded with urethane adhesive

- Continuous laminated E-glass/epoxy pre-consolidated sheets bonded with epoxy adhesive
- Resin infused carbon/vinyl ester using SCRIMP™

The treatments were as following.

- Creosote (preservative 1)
- Copper naphthenate (preservative 2)
- Diesel (carrier 1)
- Mineral spirit (carrier 2)
- Untreated control

The experiment was designed as a split-plot treatment arrangement in completely random (Steel *et al.* 1997, Snedecor and Cochrane 1989, Little and Hills 1978). Each treatment was replicated four times. In this part of the thesis, only the results of the untreated control samples were used. Four glulam billets of southern yellow pine having the dimensions of 610 x 125 x 110 mm (length x width x height) were reinforced using the SCRIMP™ process. The glulams were planed using 10 m/min planer feeding speed. Within the next one hour, the glulams were treated with n-HMR. The HMR spread rate was 146 g/m² and the HMR solids content was 5 %. After application of HMR, the billets were stored at standard conditions for 24 hours. After conditioning, the FRP layer was stacked. One layer of E-glass/CSM was used followed by thirty layers of E-glass VEW260 unidirectional woven fabrics. The total thickness of the FRP layer was approximately 19 mm. The billets were vacuum infused using the SCRIMP™ process as

described in Chapter 4.3.1 of this thesis. Vinyl ester resin and catalyst was used in a mixing ratio of 100:1 by weight. A total amount of 2.5 kg resin was used. After curing over night, the vacuum bag was removed and the wood-FRP glulams were stored at standard conditions for at least one week. After conditioning, five slices (thickness 51 mm) were cut from each billet. The cutting of the slices was carried out in two steps. In the 1st step, the FRP layer was cut using a diamond circle blade. In the 2nd step, the wood glulam was cut on the band saw. A slice is shown in Figure 14 (Chapter 4.3.1). For each treatment combination a single slice was randomly selected from each of the four billets giving a total number of four slices. After assigning all treatment combinations, the slices were treated in a treatment cylinder. The treatment process is described in Herzog *et al.* (2003). The durability test was carried out according to ASTM D 2559 (1998) and is described as following.

Cycle 1

(1) vacuum-soak in water at 635 mm mercury for 20 minutes

(2) pressure-soak in water at 520 kPa pressure for one hour

(3) repeating events (1) and (2)

(4) drying at 65°C for 21-22 hours

Cycle 2

(1) steaming at 100°C for 90 minutes

(2) pressure-soak in water at 520 kPa for 40 minutes

(3) repeating (4) in cycle 1

Cycle 3

(1) repeating events in cycle 1

The percentage of delamination was measured on each of the two FRP-wood bondlines of the slice to the nearest 0.25 mm. A single delamination value was expressed as a percentage of the total bondline length (approximately 125 mm). The mean of the delamination percentage of the two sides of each slice was determined and used for the ANOVA.

3.4. Results and Discussion

3.4.1. Shear Strength and Wood Failure of SCRIMP™ Reinforced Laminates

This experiment is described in more detail in Herzog *et al.* (2003). The results shown in this chapter contain only untreated control samples. Preservative treated and carrier treated samples are not discussed here. The experiment showed successful results. Appendix Tables C1-C4 show the shear strength and percentage of wood failure for both dry and wet conditions. Herzog *et al.* (2003) provided unbalanced data on half of the produced laminates. The number of shear blocks per laminate varied from one to three. This unbalance affected the results to a certain extent. As it can be seen e.g. in Appendix Table C1 the variation within a single laminate is quiet large. Laminate 2 had one shear block with low shear strength (6.11 MPa) and one with high shear strength (15.30 MPa). The average shear strength for this laminate was 10.71 MPa (Appendix Table C1). Laminate 1, however, had only one observation with 12.57 MPa. The experiment was

originally designed that way that a good estimate of the response variables (shear strength, wood failure) would be provided. The dimensions of the FRP-laminates (610 x 125 x 38 mm) and the used split-plot design limited the number of subsamples (shear blocks) per laminate down to two. Two shear blocks per laminate would provide at least a good estimate of the true strength performance of the laminate, whereas only one shear block would not be sufficient. In conclusion, the unbalanced datasets led into biased results on all response variables. Table 14 summarizes the results. It lists the means of both the shear strength and percentage of wood failure for all laminates for both test conditions.

Table 14. Summary of the Bond Quality for Normal Test Conditions

Laminate	Shear Strength		Wood Failure	
	Dry	Wet	Dry	Wet
	MPa	MPa	%	%
1	12.57	7.91	0.0	85.0
2	10.71	7.96	50.0	97.5
3	14.66	9.12	55.0	95.0
4	6.68	4.97	22.5	62.5
Mean	11.15	7.49	31.9	85.0
Stand Dev	3.4	1.8	26	16
COV (%)	30	24	80	19

Even though the datasets were unbalanced and might not provide the best estimates of the response variables, the results can be interpreted. Table 14 shows a higher shear strength under dry conditions (11.15 MPa) and a lower shear strength under wet conditions (7.49 MPa). Under dry test conditions, the failure at rupture occurred mostly in the region of the chop-strand mat (CSM layer) with some extension to the wood layer (Figure 29). Figure 29 shows the shear area on the FRP-layer of five shear

blocks. The percentage of wood failure ranged from 0 to 100 %. For this reason, the wood failure dry had a mean of about 32 % (Table 14). The wood failure under wet conditions was higher and reached 85 %. This was because of the lower shear strength of wood at higher moisture content (Tsoumis 1991, Haygreen and Bowyer 1989, Kollmann *et al.* 1975, Kollmann and Côte 1968). In conclusion, both the shear strength at dry and at wet conditions met the requirements of structural FRP-to-wood bondings on softwood. The shear strength at wet conditions was above the critical shear strength of 6 MPa.

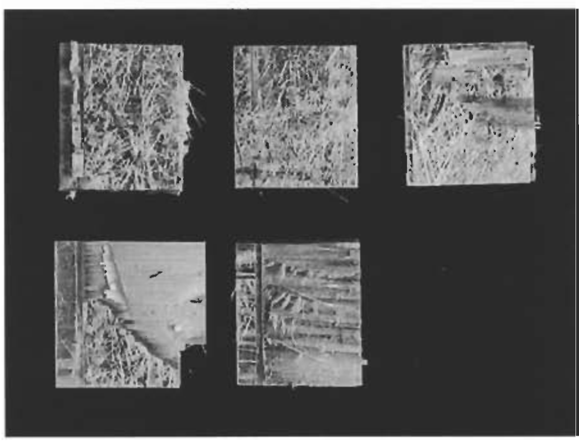

Figure 29. Shear Area of SCRIMP™ Reinforced Shear Blocks

3.4.2. Shear Strength and Wood Failure of Heat-Accelerated Dried SCRIMP™ Reinforced Laminates

This experiment was designed to shorten the entire SCRIMP™ process. Using IR heat reduced the HMR drying time to 15 minutes compared to 24 hours under standard conditions (23±2°C and 65 % RH). The results are shown in the Appendix Tables C5 and C6. Compared to standard dried laminates (Chapter 3.4.1), both the shear strength and wood failure for both conditions were in the same range. The shear strength dry was

found to be 9.31 MPa and the shear strength at wet conditions was 6.63 MPa (Table 15). The percentage of wood failure on IR heat dried laminates followed the same trend as standard dried samples. A lower wood failure dry (45 %) and a higher wood failure wet (69 %) are similar to standard dried samples. The total time of producing a FRP-wood laminate using SCRIMP™ was reduced by 24 hours. Table 16 summarizes the results of both HMR drying procedures.

Table 15. Summary of the Bond Quality for Heated Test Conditions

Laminate	Shear Strength		Wood Failure	
	Dry	Wet	Dry	Wet
	MPa	MPa	%	%
1	9.69	5.88	16.7	71.7
2	7.19	4.79	70.0	75.0
3	11.05	9.21	48.3	60.0
Mean	9.31	6.63	45.0	68.9
Stand Dev	2.0	2.3	27	8
COV (%)	21	35	60	11

Table 16. Summary for Both Drying Methods

Drying Method	Value	Shear Strength (MPa)		Wood Failure (%)	
		Dry	Wet	Dry	Wet
Standard (23±2°C, 65%RH)	Mean	11.15	7.49	32	85
	COV (%)	30	24	80	19
IR Heat (15 min, 60°C)	Mean	9.31	6.63	45	69
	COV (%)	21	35	60	11

The wood failure pattern followed the same trend as shown in Figure 29. On Samples having a low wood failure, the rupture during breakage occurred in the CSM-layer. All three laminates were found to be completely infused.

3.4.3. Delamination of SCRIMP™ Reinforced Glulams

This experiment is also described in more detail in Herzog *et al.* (2003). The results shown in this chapter contain only untreated control samples. Preservative treated and carrier treated samples are not discussed here. The experiment showed successful results. Table 17 summarizes the results of the experiment. The delamination of untreated slices varied from 0-12.7 % and the average delamination was 5.2 %. Vick and Okkonen (1997) and Vick *et al.* (1995) set the maximum delamination to 5 % for softwoods, which is also in accordance with ASTM D 2559 (1998). Although this experiment showed a higher delamination, it can be concluded that the E-glass/vinyl ester reinforcement using SCRIMP™ is potentially able to meet the 5 % mark. In general, the durability test is a very severe test. The FRP-wood bondline is exposed to an enormous stress caused by shrinkage and swelling. The accelerated test of ASTM D 2559 (1998) is designed for testing the durability of wood-to-wood bonding, but this is not the case, here. The bonding of a very rigid and dimensional stabilized FRP layer (Daniel and Ishai 1994) to a strongly hygroscopic and, therefore, dimensionally unstable material such as wood (Kollmann and Côte 1968) will cause stresses in the bondline interphase as the results of hygrothermal cycling. In my opinion, the maximum delamination of FRP-to-wood bonding could be increased to 10 % without any safety concerns.

Table 17. Delamination of the Wood-FRP Interphase

Laminate	Delamination (%)
1	0.0
2	0.0
3	8.0
4	12.7
Mean	5.2
Stand Dev	6
COV (%)	121

3.4.4. Temperature in the Wood-FRP Bondline

Recalling the experiments carried out on SCRIMP™-reinforced laminates it was obvious that vinyl ester resin cures exothermically. After reaching the gelling point, the vinyl ester resin generates heat. This heat leads to a high surface temperature of the FRP-layer and can be determined by touching the vacuum bag. The amount of heat generated during crosslinking accelerates the styrene's polymerization (Burchill and Pearce 1996). Zhao *et al.* (2001) measured temperature peaks up to 110°C on certain regions of structural E-glass/vinyl ester resin-composites infused with SCRIMP™.

A small experiment was conducted to evaluate the temperature in the bondline between the FRP-layer and the wood laminate. A thermocouple (K-type) connected to a Fluke 51-Thermometer was placed in the center of the bondline of a FRP-wood laminate. Two FRP-layer thicknesses were tested. One sample had thirty layers of VEW260 unidirectional fabrics used in all SCRIMP™ experiments mentioned above. The final thickness of the FRP layer was 19 mm. Another sample had sixty layers of the same fabric and the final thickness was approximately 35 mm. The flat-sawn wood board (southern yellow pine) had the dimensions of 610 x 125 x 19 mm (length x width x

thickness). The thermocouple was placed in between the FRP and the wood laminate and the temperature was continuously recorded. Both experiments were conducted at room temperature (20-24°C) and a relative humidity of 50-60 %. The infusion was carried out in a ventilated hood. The FRP preparation and vacuum bagging were carried out as described in Chapter 4.3.1. As resin, 2.5 kg of Derakane 411-C-50 were used and 2 % catalyst by weight was added to the resin solution.

Figure 30 shows the results. Clearly, it can be seen that a large amount of heat was generated during the curing reaction. The 30-ply laminate had a temperature peak of a approximately 60°C and the 60-ply laminate attained 80°C. This shows that the amount of resin involved in the reaction increased with increasing the number of layers, respectively the thickness of the FRP layer. Something else was also noticed. In the resin reservoir (PE bucket), the vinyl ester resin was completely gelled after 30-45 minutes, whereas in the vacuum bag, the FRP-layers on both samples were gelled after approximately 150-210 minutes. The curing process started in the resin reservoir, moved on along the resin tube and continued into the metal coil. The curing of the FRP-layer in the vacuum bag and the resin curing within the vacuum tube took place last. For this reason, the curing within the FRP-wood bondline took place much later, respectively after 150-210 minutes. The resin curing is not finished when the temperature peak is reached, but the resin is completely gelled and no resin flow is taking place anymore. After reaching the temperature peak, the bondline cooled down to ambient temperature slowly.

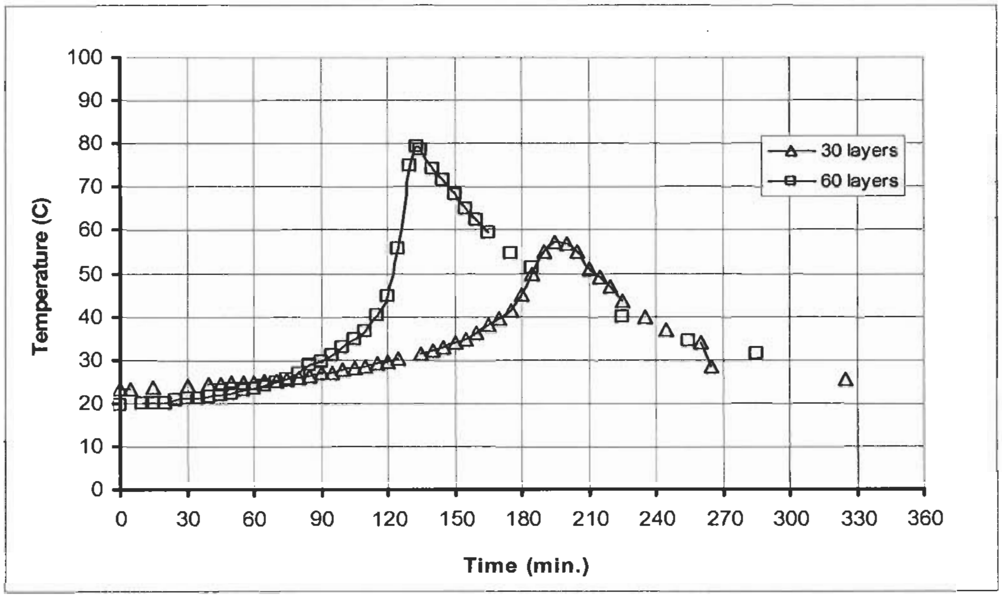

Figure 30. Temperature in the Wood-FRP Bondline

In conclusion, this experiment showed a high temperature peak in the FRP-wood bondline. The more vinyl ester resin involved in the curing reaction, the more heat is released. Furthermore, the released heat may impact the lateral moisture distribution within the wood part of the composite. A severe moisture shift in the direction to the core or cooler parts of wood member may take place. This moisture shift creates a pre-stressed FRP-wood bondline caused by shrinkage of the wood region close to the FRP layer. In my opinion, further research is necessary here.

3.5. Conclusions and Recommendations

The following conclusions and recommendations can be stated.

1. The reinforcement of wood members using the SCRIMP™ process showed satisfying results in terms of bondline quality and durability performance. The

shear strength in compression was consistently high and above the minimum required shear strength of 6 MPa for structural adhesives. The percentage of wood failure was lower under standard test conditions and higher for the water-soaked condition. The resistance of the FRP-wood composite against heat-accelerated exposure was high and the percentage of delamination was close to 5 %. These results propose a good performance of E-glass/vinyl ester resin-reinforced structural wood members using the SCRIMP™ process. The HMR drying using IR heat reduced the total production time of manufacturing a SCRIMP™-reinforced wood-FRP composite by 24 hours. Compared to the standard drying method of HMR, the same bonding quality was achieved.

2. The SCRIMP™ process was also found to have some weaknesses. It is a very sophisticated technique containing numerous steps. The total production time of a glulam billet having a length of approximately 600 mm took about 36 hours. The preparation of the FRP layer including (a) HMR-priming, (b) HMR-drying using IR-lamps, (c) cutting and stacking the E-glass fabrics, and (d) adjusting the peel ply, flow medium and metal coil, took approximately three hours. The following sealing of the vacuum bag and the adjusting of the tubes took usually another one hour. The infusion of the FRP-layer was done in only 20-40 minutes, followed by curing under vacuum for the next 4-6 hours. The final cure took place during the following 24 hours. And finally, the removal and disposure of (a) the vacuum bag and tubes, (b) the peel ply and flow medium, and (c) the metal coil, took another one hour. In my opinion, this production time is too long and cost inefficient for mass production. Another problem has to be kept in mind. After curing, the FRP

had no perfectly smooth surface (see Figure 14). The edge on both sides of the FRP-layer overspread the sides of the glulam billet. In addition, parts of the billet were coated with a thin layer of cured vinyl ester resin. Because of the vacuum, the resin traveled through gaps and foldings of the vacuum bag and coated the billet surface. This thin layer of cured vinyl ester resin is chemically resistant (Burchill and Pearce 1996). The overspreading FRP layer and the vinyl ester coating have to be removed before treatment with wood preservatives. According to Eaton and Hale (1993), the bark, in this case resin coating, has to be removed from the surface before preservative treatment. The toughness of both E-glass fibers and cured vinyl ester resin requires the use of diamond knives. Any post-preparation elevates the total cost.

3. The incomplete infusion of one FRP-laminate must be reason for concern about the reliability and safety of the SCRIMP™ process for wood-FRP reinforcement. The resin flow depends on many factors, such as ambient temperature, fiber surface, chemical reactivity of the resin, curing behavior, etc. These factors change and sometimes lead into incomplete infusion of the part. If this incomplete infusion is not noticed and the reinforced part gets into application, a catastrophic damage can be expected. This research was done on small samples. The infusion of a small sample can be carried out with greater success then of a large-scaled member. The length of the resin's traveling path was short and the infusion could be easily carried out. A large-scale glulam beam having a length of 20 m or more will require a totally different infusion strategy. In my opinion, it will be very difficult to provide an appropriate sealed vacuum bag without causing leaks when

the large-scale beam has a weight of 2000 kg or more. The high temperature peak in the wood-FRP interphase must be reason for concern, too. Depending on the FRP-layer thickness, the released heat may shift wood moisture away from the bondline into the core of the wood member. This moisture shift can cause a pre-stressed wood-FRP bondline and may negatively impact the bonding quality. In my opinion, the investigation of this temperature regime within the bondline has to be carried out in future research.

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Chapter 4

SHEAR STRENGTH AND WOOD FAILURE OF VINYL ESTER RESIN BONDED WOOD LAMINATES

4.1. Introduction

Vinyl ester resin is widely used for fiber reinforced polymers (FRP). It is used in the boat industry, e.g. TPI Composites, Inc., but also it is used for wood-FRP composites presented in Chapter 3. Compared to other structural adhesives, vinyl ester resin is cheap ($ 3.30/kg) and it is easy to mix, because of a two-component-resin system containing vinyl ester resin and catalyst. The used FPL-1 epoxy adhesive in Chapter 2 contained of four components that are epoxy resin, benzyl alcohol, silica and TET hardener.

Lopez-Anido *et al.* (2000) bonded E-glass stitched fabrics impregnated with vinyl ester resin to eastern hemlock glulam panels using the wet-lay up method and compaction was achieved through vacuum bagging. The manufactured wood-FRP composite showed a high shear strength in compression and a high percentage wood failure. In addition, the wood-FRP composite withstood cyclic delamination. Lopez-Anido *et al.* (2002a), Lopez-Anido *et al.* (2002b), Herzog *et al.* (2003), and the results presented in Chapter 3 showed great performance of SCRIMP™ reinforced structural wood members. Wood-FRP composites using the SCRIMP™ process described in Chapter 3 showed a high shear strength in compression combined with a high percentage wood failure. Derakane 411-C-50 vinyl ester resin used for SCRIMP™ seems to penetrate the wood cells, maybe the

wood cell walls, too, and seems to develop a strong interlocking between the FRP matrix and wood. This interlocking effect results in a good bonding performance.

Both good bonding performance and low cost make vinyl ester resin very attractive for wood-to-FRP bonding. In all research mentioned above, the FRP-layer was applied to wood using a resin infusion method. This chapter aimed to use vinyl ester resin for bonding pre-consolidated FRP to wood. The assumption here was to use vinyl ester resin for wood-to-wood bonding and set up the manufacturing parameters for the bonding of FRP to wood. Once vinyl ester resin achieves a good bonding performance for wood-to-wood bonds, it should be possible to use vinyl ester resin for bonding pre-consolidated FRPs manufactured by continues lamination or pultrusion to structural wood members. The experiment was conducted on two wood species, which were southern yellow pine and hard maple. Two-layer laminates as described in Chapter 2 were produced and tested according to ASTM D 905 (1994). The response variables of the tests were both shear strength in compression and percentage of wood failure, and two test conditions were tested under standard conditions (23±2°C and 65 % RH) and under water-soaked conditions. Testing of wood composites according to ASTM D 905 (1994) is reliable and quick. The wood laminates were treated with n-HMR solution prior to the application of the vinyl ester resin. Different types of vinyl ester resins having a viscosity range between 50 to 2000 cPs at 24°C were used.

4.2. Materials and Testing Equipment

4.2.1. n-HMR Coupling Agent

The experiment was conducted on novolak-based HMR coupling agent. The HMR solids content was 5 % and same mixing procedure described in Chapter 2.2.1 was used. The HMR spread rate was 146 g/m². Table 18 shows the ingredients used to make n-HMR.

Table 18. Ingredients of n-HMR

Ingredients	Amount of Chemical (g)
Crystalline Resorcinol	3.34
Deionized Water	90.43
3-Molar Sodium Hydroxide Solution	2.44
Formaldehyde Solution (37.1% Formalin)	
For Novolak Stage	0.95
For Final Activation Stage	2.84
Dodecyl Sulfate Sodium Salt	0.50

4.2.2. Wood Species and Wood Samples

4.2.2.1. Southern Yellow Pine

Parts of the experiment were conducted on flat-sawn southern yellow pine (*Pinus spp.*). Sample boards were cut from lumber having dimensions of 2000 x 125 x 19 mm (length x width x thickness). The boards were stored at standard conditions (23±2°C and 65 % RH) for at least eight weeks.

4.2.2.2. Hard Maple

Parts of the experiment were conducted on flat-sawn hard maple (*Acer saccharum*). The boards were stored at standard conditions (23±2°C and 65 % RH) for at least eight weeks. The dimensions of the lumber were 3000 x 125 x 19 mm (length x width x thickness). The lumber grade was "select". KARAM's Hardwood & Millwork from Bangor, ME, supplied the lumber.

4.2.3. Vinyl Ester Adhesives

Experiments using the SCRIMP™ process were carried out with Derakane 411-C-50 resin. The tests to evaluate wood-to-wood bonding used resins with a higher viscosity. The following mixing procedure was used for all vinyl ester resins. From the supplier's container, the vinyl ester was poured into a PVC or PE container. Cobalt solution in the amount of 0.1 weight-percent was added to resins that were not promoted. This solution was stirred for two minutes. The catalyst (2-butanone peroxide) was added to the resin solution in a mixing ratio between 1:100 and 1:50 by weight. This solution was stirred for 5 minutes. Immediately after stirring, the resin solution was applied. Depending on the room temperature, the gelling time of this solution was between 20-60 minutes.

The following chemicals were used for making vinyl ester resin.

- Derakane epoxy vinyl ester resin 411-C-50, containing styrene monomer, from The Dow Chemical Company, Midland, MI.

- Derakane epoxy vinyl ester resin 411-700 PATW, containing styrene monomer, from The Dow Chemical Company, Midland, MI.
- Derakane epoxy vinyl ester resin 411-35, containing styrene monomer, from The Dow Chemical Company, Midland, MI.
- 2-Butanone peroxide, ~32 wt% solution in phthalate-free plasticizer mixture (Lupersol® DHD-9*) from Sigma-Aldrich Inc., Milwaukee, WI.
- Cobalt naphthenate, solution contains 12% cobalt, from The Dow Chemical Company, Midland, MI.

4.2.4. PRF Adhesive

According to Marra (1992), phenol-resorcinol-formaldehyde (PRF) resin is one of the most used adhesives for structural wood members. PRF resin has the big advantage of developing a high bonding strength after curing at ambient conditions. Because of its wide use, this adhesive was used as a control adhesive for measuring the viscosity of vinyl ester resin. The ingredients of PRF resin are shown in Table 19. The mixing procedure was as follows. 9.6 g of catalyst were added to 18.4 g deionized water. The solution was stirred for two minutes. 72 g of PRF resin were added to the solution followed by stirring for five minutes. Within the next 2 minutes, the viscosity was continued measured until gelling (Chapter 3.5.3.1).

Table 19. Ingredients of the PRF Adhesive

Ingredients	Amount of Chemical (g)
Liquid PRF Resin	72.0
Paraformaldehyde Catalyst	9.6
Deionized Water	18.4

The following chemicals were used for making PRF resin.

- Cascophen™ AG 5620 Liquid PRF resin from Borden Chemical, Inc., Columbus, OH
- Cascoset FM-6210 Paraformaldehyde catalyst from Borden Chemical, Inc., Columbus, OH

4.2.5. Carver Laboratory Press

Parts of the vinyl ester resin experiment (Chapter 3.5) were conducted on a Carver Laboratory Press (Model B) manufactured by Fred S. Carver Inc., Summit, NJ. The press (Figure 31) had a loading range of 0-100 kN and a press area of 150 x 150 mm. Steel plates having the dimensions of 300 x 125 x 12.5 mm (length x width x thickness) and two pieces of lumber on each side were used to increase the pressing area.

Figure 31. Carver Laboratory Press

4.2.6. Press Clamps

Parts of the experiments were conducted using the press clamps described in Chapter 2 (Figure 5).

4.2.7. INSTRON Testing Frame

The shear strength and percentage of wood failure were determined on the INSTRON testing frame described in Chapter 2 (Figure 6).

4.2.8. Viscometer

The viscosity of resin was measured using the following viscometer.

- Brookfield Digital Viscometer, Model DV-I+ from Brookfield Engineering Laboratories, Inc., Middleboro, MA

4.2.9. HMR Drying Apparatus

Some HMR treated laminates were dried using the HMR drying apparatus described in Chapter 2.2.4. The same set-up was used for drying the HMR-treated wood surfaces.

4.3. Methods

Three types of vinyl ester resins were tested. The vinyl ester resins were supplied by The DOW Chemical Company, Midland, MI. The final promoting of the vinyl ester resins was done by Composite One, Inc., Arlington Heights, IL. The vinyl ester resin had a viscosity in a range between 50-2000 cPs. Table 20 shows the viscosities of the vinyl ester resins. As mentioned above, Derakane 411-C-50 having the lowest viscosity is widely used in the SCRIMP™ process. The low viscosity allows to infuse the FRP fabric using vacuum infusion. The 1st test on wood-to-wood bonding presented in this chapter used this vinyl ester resin. The conducted experiment showed good bonding performance,

but the results could not be experimentally repeated. Therefore, vinyl ester resins having a higher viscosity were also tested.

Table 20. Viscosities of the Vinyl Ester Resins

Vinyl Ester Resin	Viscosity (cPs)
Derakane 411-C-50	50
Derakane 411-700 PATW	700
Derakane 411-35	2000

4.3.1. Bond Quality of Derakane 411-C-50

This resin had the lowest viscosity and was tested first. The resin supplier determined a viscosity of 50 cPs. The 1st experiment was conducted on flat-sawn southern yellow pine. The age of the vinyl ester resin was eight months. Prior to the application of n-HMR, the boards having the dimensions of 250 x 50 x 19 mm (length x width x thickness) were planed with 10 m/min planer feeding speed. Within the next hour, the HMR solution was applied to the surface by brushing. The HMR solids content was 5 % and the HMR spread rate was 146 g/m². After the HMR solution was applied, the boards were stored at standard conditions (23±2°C and 65 % RH) for different time periods. The HMR drying time ranged from 24 to 240 hours (Table 21). After conditioning, the vinyl ester adhesive was applied. Catalyst and vinyl ester resin were mixed in a ratio of 1:50 by weight. The adhesive spread rate was 500 g/m² per bondline and the opening time was about 2 minutes. The laminates were bonded using hand-clamps used in carpentry. The clamping pressure was not controlled. For each HMR

drying time, a single two-layer laminate was produced. After curing over night, the wood-FRP laminates were stored at standard conditions for at least two days. After conditioning, 4-5 shear blocks were cut from each laminate. The shear strength and the percentage of wood failure were determined under water-soaked conditions (20 min soaking at 635 mm mercury vacuum followed by soaking under 520 kPa pressure). The percentage of wood failure was estimated to the nearest 5 %. The test was carried out according to ASTM D 905 (1994). Table 21 lists the levels of HMR drying time and the number of laminates.

Table 21. HMR Drying Times and Number of Laminates

Wood Species	HMR Age (hours)	Number Laminates
Southern Yellow Pine	24	1
	120	1
	240	1

The 2nd experiment was conducted on a vinyl ester resin no older then 1 month. The way the resin was promoted required the addition of 0.1 weight percent of cobalt solution. This experiment was thought to determine the most appropriate clamping pressure for the HMR drying experiment described in Chapter 2. Two wood species, southern yellow pine and hard maple, were used. The wood boards had the dimensions 250 x 115 x 19 mm (length x width x thickness), and were prepared and HMR treated the same way described in the 1st experiment. The laminates were bonded for 24 hours using the Carver laboratory press. Table 22 lists the number of laminates and the used clamping pressure levels. The conditioning after bonding and testing were the same as in the 1st experiment.

Table 22. Clamping Pressures and Number of Laminates

Wood Species	Clamping Pressure (kPa)				
	100	200	300	400	500
Southern Yellow Pine	4	4	4	4	4
Hard Maple	2	2	2	-	-

The 3rd experiment was conducted on another vinyl ester resin sample. This time, the resin supplier promoted and added the full amount of cobalt to the vinyl ester resin. The experiment was conducted on hard maple. Table 23 shows the experimental design. The same manufacturing procedure as described in the 1st and 2nd experiment was used.

Table 23. Vinyl Ester Resin Spread Rates, Clamping Pressures and Number of Laminates

Wood Species	Resin Spread Rate (g/m^2)	Clamping Pressure (kPa)	
		100	600
Hard Maple	500	2	2
	1000	2	2

4.3.2. Bond Quality of Derakane 411-700 PATW

Because of unsuccessful results using Derakane 411-C-50, a vinyl ester resin having a higher viscosity, Derakane 411-700 PATW (700 cPs), was used. For further increase of the viscosity, different weight percents of hydrophobic fumed silica (used for FPL1-epoxy resin, Chapter 2.2.3) were added to the vinyl ester resin. Table 24 shows the factors of the experiment. The same manufacturing procedures described above were used. Instead of using the Carver laboratory press, press clamps were used for bonding the wood laminates. The vinyl ester resin spread rate was 500 g/m^2.

Table 24. Amounts of Filler, Clamping Pressures and Number of Laminates

Wood Species	Amount of Filler (%)	Clamping Pressure (kPa)	
		200	400
Hard Maple	0	2	2
	5	2	2
	10	2	2

4.3.3. Bond Quality of Derakane 411-35

The last series of experiment was conducted on Derakane 411-35 having a viscosity of 2000 cPs. Two wood species were used. Table 25 shows the factors of the experiment. The same manufacturing procedures described above were used. Press clamps were used for bonding the wood laminates and the vinyl ester resin spread rate was 500 g/m². Before clamping, the laminates were allowed to sit open between 5 to 15 minutes.

Table 25. Opening Times, Clamping Pressures and Number of Laminates

Wood Species	Opening Time (min)	Clamping Pressure (kPa)		
		100	200	700
Southern Yellow Pine	5	2	1	2
	10	-	1	-
	15	-	1	-
Hard Maple	5	2	-	2

At this point of testing, many factors had been examined. The previous tests included following factors.

- Vinyl ester resin type

- Viscosity
- Spread rate
- Clamping pressure
- Opening time
- Weight percent Filler
- Wood species

All these factors didn't improve the bonding quality. These factors are important to know when a new adhesive system is under investigation. Marra (1992) states the importance of these factors, too. All tests showed unsuccessful results which are discussed in the following results and discussion section. Recalling the SCRIMP™ results described in Chapter 3 of this thesis, only one parameter has not been changed. All wood-to-wood bonding tests were conducted at ambient temperature. As shown in Chapter 3.5 (Temperature in the Wood-FRP Bondline, Figure 30), vinyl ester resin cures exothermically and a large amount of heat is released. Based on this circumstance, an experiment was conducted where the laminates were bonded in a drying oven at 60°C.

Wood boards from southern yellow pine and hard maple having dimensions of 600 x 115 x 19 mm (length x width x thickness) were dried in a drying oven at 60°C for one week. After drying, the boards were planed and laminates having dimensions of (250 x 115 x 19 mm (length x width x thickness) were cut. n-HMR was applied followed by drying for 15 minutes using the HMR drying apparatus. Immediately after drying, the laminates were bonded within the oven using press clamps and a clamping pressure of

200 kPa. The laminates were cured for 24 hours followed by cutting the shear blocks. Table 26 shows the number of laminates tested per wood species.

Table 26. Curing Temperatures and Number of Laminates

Wood Species	Curing Temperature (°C)	Number of Laminates
Southern Yellow Pine	60	4
Hard Maple	60	4

4.3.4. Testing of the Shear Blocks

The shear strength and percentage wood failure were determined on the INSTRON testing frame. The same loading speed and equations (Equations 5 and 6) were used as described in Chapter 3.3.5.

4.3.5. Viscosity of Derakane 411-35

Marra (1992) states the importance of the resin's viscosity. The viscosity regulates the resin penetration rate and gives the resin "body". The viscosity can be adjusted by adding fillers to the resin. The experiments carried out in the previous sections were unsatisfying as described in the following results and discussion section. To check if the viscosity of Derakane 411-35 vinyl ester resin is similar to PRF resin, a

small experiment was conducted. The viscosity of Derakane 411-35 was compared with a widely used PRF resin, such as Cascophen™ AG 5620.

The viscosity of both resins was measured without catalyst or hardener. After that, the catalyst and the hardener were added to the resin solutions respectively, and the viscosity was measured continuously until gelling. In addition, the temperature of the reaction was recorded. For Derakane 411-35, the mixing ratio of vinyl ester resin and catalyst was 100:1 by weight. For Cascophen™ AG 5620, the mixing ration is given in Chapter 4.2.3.2. The total weight of the resin solution was approximately 200 g. The viscosity was measured using the Brookfield Digital Viscometer and spindle number three was used.

4.4. Results and Discussion

4.4.1. Bond Quality of Derakane 411-C-50

Samples having different HMR drying times at standard conditions (23±2 C° and 65 % RH) showed a high bonding quality. Table 27 lists the results of shear strength and wood failure tested under water-soaked conditions. The shear strength reached approximately 7 MPa, which is similar to the shear strength of SCRIMP™ reinforced laminates that was determined with values between 7.5 MPa (standard drying) and 6.6 MPa (IR heat drying) (see Chapter 3). The wood failure was even higher then SCRIMP™ reinforced laminates and was almost 100 %. These excellent results promised a good bonding quality using vinyl ester resin for wood-to-wood bonding. Further research

described in the following sections could not repeat these results. This can have several reasons.

1. The vinyl ester resin used in this experiment was drawn from an old resin sample. The vinyl ester resin was approximately eight months old. The resin's chemical structure and curing behavior might have changed dramatically. Maybe the resin curing process took place in a shorter period of time because of the changed chemical resin structure. All other tests were conducted on fresh-promoted vinyl ester resin that seemed to cure differently.
2. This experiment used two weight percent catalyst. The combination of both older resin age and the higher amount of catalyst added to the vinyl ester resin could have contributed to a better bond performance.

Table 27. Shear Strength and Wood Failure on Derakane 411-C-50

Wood Species	HMR Age (hours)	Number Laminates	Number Shear Blocks	Shear Strength (MPa)	Wood Failure (%)
Southern Yellow Pine	24	1	5	6.4	97
	120	1	5	7.0	100
	240	1	4	6.5	100

The following experiment had to evaluate the most appropriate clamping pressure for Derakane 411-C-50. Table 28 lists the shear strength in MPa for the two wood species and the five levels of clamping pressure. Many laminates failed and delaminated when the shear blocks were cut. Some laminates broke apart using only hand force. Table 28 shows the highest shear strength measured on the four replications per treatment. For example, on southern yellow pine bonded using 100 kPa clamping pressure, the shear

strength under ambient conditions was 4.3 MPa for the best-performing laminate, whereas the shear strength under water-soaked conditions was 2.0 MPa. Table 29 shows the percentage of wood failure on the same laminates. In conclusion, both shear strength and wood failure didn't reach the minimum levels of bond performance for structural wood adhesives. On hardwood, a structural wood adhesive should reach, under water-soaked conditions, a minimum shear strength of at least 6 MPa and a wood failure of at least 50 %.

Table 28. Shear Strength in MPa at Different Clamping Pressures on Derakane 411-C-50

Wood Species	Condition	Number Laminates	Clamping Pressure (kPa)				
			100	200	300	400	500
Southern Yellow Pine	Dry	4	4.3	Failed	2.8	1.6	Failed
	Wet	4	2.0	Failed	1.3	0.3	Failed
Hard Maple	Dry	2	Failed	Failed	Failed	N/A	N/A
	Wet	2	Failed	Failed	Failed	N/A	N/A

Table 29. Wood Failure in Percent at Different Clamping Pressures on Derakane 411-C-50

Wood Species	Condition	Number Laminates	Clamping Pressure (kPa)				
			100	200	300	400	500
Southern Yellow Pine	Dry	4	40	Failed	25	5	Failed
	Wet	4	33	Failed	20	5	Failed
Hard Maple	Dry	2	Failed	Failed	Failed	N/A	N/A
	Wet	2	Failed	Failed	Failed	N/A	N/A

Laminates that failed always had the same failure patterns. The bondline showed incomplete curing and liquid resin residuals were found sitting on the surface. The resin seemed to penetrate deeply into the wood substrate and no bondline layer as known from

epoxy adhesives or PRF adhesives was noticeable. The next experiment was conducted with increased adhesive spread rate. As shown in Table 30, all laminates failed and delaminated when the shear blocks were cut on the table saw. The failure patterns were exactly the same as mentioned above.

Table 30. Bond Performance of Derakane 411-C-50

Wood Species	Resin Spread Rate (g/m^2)	Condition	Number Laminates	Clamping Pressure (kPa)	
				100	600
Hard Maple	500	Dry	2	Failed	Failed
	1000	Dry	2	Failed	Failed

4.4.2. Bond Quality of Derakane 411-700 PATW

To increase the bond performance, it was decided to use a vinyl ester resin having a higher viscosity. At that moment, it was assumed that the viscosity is mainly responsible for the bonding performance of any adhesive system. Table 31 lists the results. Laminates bonded with Derakane 411-700 PATW with no filler delaminated when the shear blocks were cut. The bondline showed an incomplete curing reaction and some liquid resin residuals were found on the wood surface. Adding filler did not improve the bonding strength. A resin layer was created at the bondline, but without providing any bond strength. No liquid resin residuals were found on samples bonded with filler.

Table 31. Bond Performance of Derakane 411-700 PATW

Wood Species	Amount of Filler (%)	Condition	Laminates	Clamping Pressure (kPa)	
				200	400
Hard Maple	0	Dry	2	Failed	Failed
	5	Dry	2	Failed	Failed
	10	Dry	2	Failed	Failed

4.4.3. Bond Quality of Derakane 411-35

The last set of experiments was conducted on Derakane 411-35 vinyl ester resin. This vinyl ester resin was promoted by Composite One, Inc., and the gelling time was set to 20 minutes when one weight percent catalyst is added. According to Composite One, Inc., for a vinyl ester resin having such a high viscosity (in this case 2000 cPs), the gelling time can not be elongated further. The results presented in the last two sections showed low bonding performance and incomplete curing behavior of the vinyl ester resin. To improve the bonding strength, the vinyl ester resin having the highest viscosity, such as Derakane 411-35, was tested in this section.

4.4.3.1. Bonding Under Ambient Conditions

The results of the bonding of laminates are shown in Tables 32 and 33. Under dry test conditions (23±2°C and 65 % RH), laminates bonded with 200 kPa clamping pressure performed well at a short opening time, but failed or had low bonding performance when the opening time was extended. Laminates bonded either with higher or lower clamping pressure then 200 kPa failed completely. Under water-soaked test

conditions, the bonding strength was low for all laminates and many laminates failed entirely.

Table 32. Shear Strength in MPa of Derakane 411-35

Wood Species	Opening Time (min)	Conditions	Clamping Pressure (kPa)		
			100	200	700
Southern Yellow Pine	5	Dry	Failed	10.4	Failed
		Wet	Failed	5.0	Failed
	10	Dry	N/A	3.0	N/A
		Wet	N/A	3.3	N/A
	15	Dry	N/A	Failed	N/A
		Wet	N/A	Failed	N/A
Hard Maple	5	Dry	Failed	N/A	Failed
		Wet	Failed	N/A	Failed

Table 33. Wood Failure in Percent of Derakane 411-35

Wood Species	Opening Time (min)	Conditions	Clamping Pressure (kPa)		
			100	200	700
Southern Yellow Pine	5	Dry	Failed	21	Failed
		Wet	Failed	33	Failed
	10	Dry	N/A	0	N/A
		Wet	N/A	0	N/A
	15	Dry	N/A	Failed	N/A
		Wet	N/A	Failed	N/A
Hard Maple	5	Dry	Failed	N/A	Failed
		Wet	Failed	N/A	Failed

4.4.3.2. Bonding in the Drying Oven

In recapitulation, the laminates were kept in the drying oven for seven days. After drying, the laminates were treated with n-HMR followed by drying under IR-heat for 15 minutes. Immediately after that, the laminates were bonded in the drying oven at 60°C.

This experiment was supposed to succeed, because of the good results on SCRIMP™. Unfortunately, this experiment failed, too. Table 34 shows the results. All laminates delaminated during shear block cutting or could be broke apart with hand force. The failure pattern was different to the sections discussed before. No liquid vinyl ester resin residuals were found on the bondline surfaces. All vinyl ester resin penetrated the wood substrate and no bondline resin layer was created.

Table 34. Bonding Performance of Heat-bonded Laminates

Wood Species	Curing Temperature (°C)	Number of Laminates	Bonding Performance
Southern Yellow Pine	60	4	Failed
Hard Maple	60	4	Failed

4.4.3.3. Viscosity of Derakane 411-35

The viscosity was measured on two adhesives. For Derakane 411-35, the initial viscosity before adding the catalyst was determined with 4290 cPs at 24°C. After adding catalyst in the amount of one weight percent, the viscosity dropped to 3882 cPs. From here, the viscosity was measured continuously until gelling. Table 35 shows the result. For the next 11-15 minutes, the viscosity was stable, but after 16 minutes the resin started gelling followed by a spontaneous increase of the viscosity. During measurement, the spindle speed in rounds per minute (RPM) had to be reduced. At the gelling point, the resin temperature increased, too. For Cascophen™ AG 5620, the initial viscosity of the liquid PRF resin was determined with 4014 cPs at 24°C. After adding water and catalyst

according to the mixing ratio given in Table 19 (Chapter 4.2.3.2), the viscosity dropped down to 774 cPs. After adding water and catalyst, the temperature increased spontaneously to 31°C and further to 35°C, because of exothermic reaction of the dissolving paraformaldehyde in water (Marra 1992). During the next 5-6 minutes, the viscosity increased slowly, but after 9 minutes, the adhesive started to gel and the viscosity rose spontaneously. Table 35 shows the results. Figure 32 shows the viscosity over time for both adhesives.

Table 35 Viscosities of Derakane 411-35 and Cascophen™ AG 5620 During Gelling

Time	Derakane 411-35			Cascophen AG 5620		
	Viscosity	RPM	Temperature	Viscosity	RPM	Temperature
min	cPs	1/min	C	cPs	1/min	C
2	3882	20	24	774	100	31
6	3534	20	24	1000	100	35
9	3600	20	24	2150	50	
11	3606	20	24	8000	10	
16	4272	20	25	96000	1	
18	5700	20				
19	10000	10				
20	24000	5				

The conclusions of this experiment are as follows.

1. The viscosities of both Derakane 411-35 vinyl ester resin and PRF adhesive, are in a similar range. In my opinion, the vinyl ester resin's viscosity is at least not too low. This means the vinyl ester resin can be applied to wood without loosing too much resin solution because of absorption into the bondline surface. Now the big question can be stated as follows. Does the viscosity of vinyl ester resin negatively impact the resin penetration into the wood substrate as seen in the last experiments? All experiments showed a deep penetration of the vinyl ester resin

into the wood. The bondline was almost entirely dry, only a few liquid residuals were left on the surface. It seemed that high quantities of the vinyl ester resin were absorbed by the wood. But on the other hand, the viscosity of PRF adhesive was even lower then that of the vinyl ester resin. Therefore, there must be other reasons for the weak bonding performance of vinyl ester resin for wood-to-wood bonds. It seems that the entire bonding linkages between the resin matrix and the wood substrate do not occur. SCRIMP™ reinforcements bond well to wood, but vinyl ester resin can not be used for wood-to-wood bonding.

2. The gelling behavior is similar for both adhesives, Derakane 411-35 and Cascophen™ AG 5620. The gelling time of both adhesives is between 15-20 minutes, which is good for any application. A shorter gelling time would be troublesome, because it would not give the applicator enough time to apply the adhesive before gelling. Now, the resin promoter, which was Composite One, Inc., stated that it is quite impossible to further increase the viscosity of vinyl ester resin in general. A further viscosity increase would lead into a dramatic shortening of the gelling time of such resins. Derakane 411-35 has one of the highest viscosities possible for commercial vinyl ester resins. A gelling time shorter then 10-15 minutes is unacceptable for industrial application. For example, FPL-1 epoxy resin has a similar gelling time like PRF resin, but is thixotropic with a higher viscosity. In conclusion, the viscosity is not this important for the bonding performance of wood products. Together with the molecular weight of the adhesive, it regulates the penetration into the substrate to

a certain degree, but other factors such as the creation of bond linkages and the general curing process are much more important.

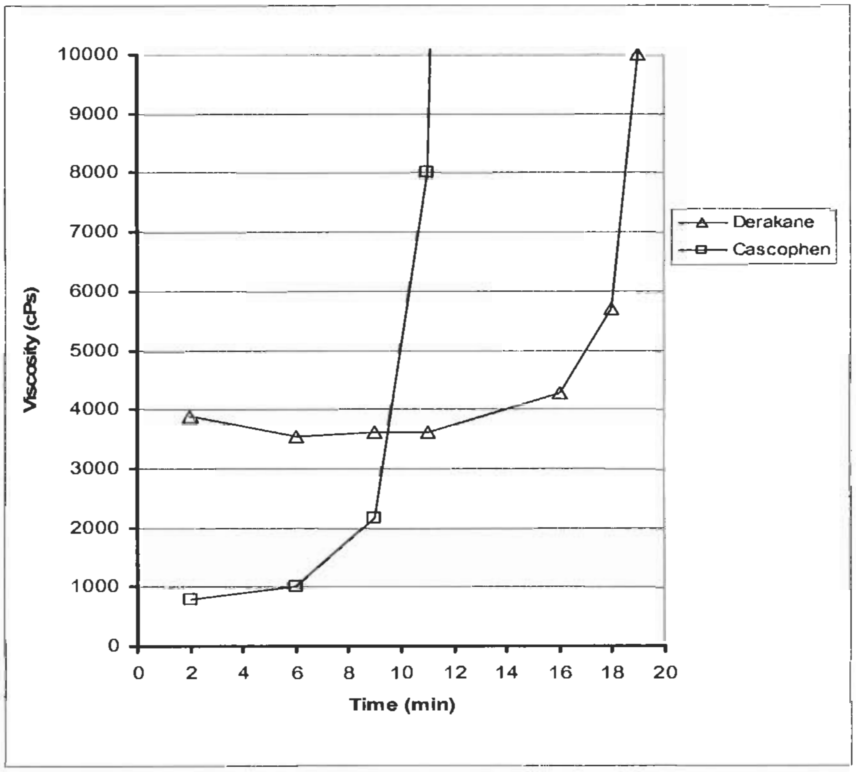

Figure 32. Viscosity During Gelling of Derakane 411-35 and Cascophen™ AG 5620

4.5. Conclusions and Recommendations

The following conclusions and recommendations can be stated.

1. The wood-to-wood bonding performance of three types of vinyl ester resins showed unsuccessful results. Varying the physical parameters of adhesive bonding such as clamping pressure, spread rate, resin viscosity, etc., didn't affect the bonding performance. Many laminates failed and delaminated without

development of any shear strength. Only a few laminates could be bonded successfully, but the shear strength and wood failure were low. The reason for this variation in the strength performance was most likely because of the age of the resin. Older vinyl ester resin tended to bond wood-to-wood better. This might be caused by a higher degree of polymerization. The same trend was noticed on fresh promoted resins left in the resin batch for a longer period of time. In this case, the catalyst started the curing reaction and at the right moment, the vinyl ester resin was applied to the wood surface and cured instantly. This explains the better bonding performance of some of the laminates. But these outliers do not mean that vinyl ester resin can be used successfully for wood-to-wood bonding. In any bonding process, the gelling time is a very important figure. If it is too short, the application will be troublesome and very risky.

2. In my opinion, the investigation of vinyl ester resin used for wood-to-wood bonding can not be carried out only by varying the physical bonding parameters of adhesion. The failing laminates indicate a weakness of vinyl ester resin in general. Only a few laminates were bonded successfully under a certain circumstance, which was most likely an advanced degree of polymerization. In this state, vinyl ester resin creates linkages between the resin matrix and the substrate. This polymerization can not be controlled. The vinyl ester resin may reach this point of polymerization sometimes sooner, and sometimes later. Therefore, the results are very unpredictable. For this reasons, the chemical properties of vinyl ester resin have to be adjusted first, before continuing with testing. To use vinyl ester resin for wood-to-wood bonding, it has to be

determined if vinyl ester resin is able to be used under the circumstances of wood adhesion in general. It may be that the SCRIMP™ reinforcement is a special case where vinyl ester resin can create bondings to the wood substrate. But this may not be the case for wood-to-wood bonding, too. It is recommended to cooperate any future wood bonding research on vinyl ester resin with the manufacturing company, such as The Dow Chemical Company, and the Department for Chemistry. The chemistry of vinyl ester resin has to be changed to improve wood-to-wood bonding. The use of additives, initiators, etc. could improve the vinyl ester resin's properties, but this is beyond the scope of this thesis.

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APPENDICES

Appendix A.

Statistical Data of the Experiment to Reduce the HMR Drying Time (Complete Datasets)

Table A1. SAS File

```
/*DRYING OF N-HMR - EPOXY RESIN (FPL-1) ON HARD MAPLE
5x2x2 FACTORIAL W/ 7 REPS, CARRIED OUT: FALL 2002;
FILENAME: DRYHMR1 SAS; 1=5MIN, 2=10MIN, 3=15MIN, 4=20MIN, 5=24HOURS*/
OPTIONS LINESIZE=72;
DATA HMR1;
INPUT T S C SHE_D SHE_W WF_D WF_W;
SHEAR_D=SHE_D*0.0068948;
SHEAR_W=SHE_W*0.0068948;
CARDS;
1 1  5 2789  515  80   7
1 1  5 2282  429  97   0
1 1  5 3113  471  58   3
1 1  5 2752  614  68  17
1 1  5 2484  794  90  38
1 1  5 2668  400  63   0
1 1  5 2630  595  37   0
1 1 10 2721  702  92  37
1 1 10 2864  599  28  53
1 1 10 2702  627  92  13
1 1 10 2500  493  53  15
1 1 10 2638  625  73  10
1 1 10 3118  815  77  47
1 1 10 1929  605  43  12
1 2  5 3031  575  77   2
1 2  5 2528  727 100  10
1 2  5 2653  592  77   3
1 2  5 2608  849  65  35
1 2  5 3258  513  95   8
1 2  5 2813  602  82  13
1 2  5 1406  517  27   7
1 2 10 3128  239  47   0
1 2 10 2056  634  25  20
1 2 10 2854  523  38   0
1 2 10 2377  549  70  13
1 2 10 2867  617  63   3
1 2 10 1395  356  32   0
1 2 10 3238  679  70   8
2 1  5 3169  826  70  60
2 1  5 3169  891 100  67
2 1  5 2630 1105  98  75
2 1  5 3203  978  57  28
2 1  5 3259 1062  78  60
2 1  5 3349 1020  53  43
2 1  5 2539 1093  97  63
2 1 10 2595  914  75  32
2 1 10 3663 1237  95  47
2 1 10 2794 1277  62  48
```

Table A1. Continued

2	1	10	2779	1149	88	77
2	1	10	2697	1252	80	65
2	1	10	2932	899	83	53
2	1	10	2208	757	30	18
2	2	5	3115	604	87	23
2	2	5	3027	940	87	68
2	2	5	2845	811	83	7
2	2	5	2818	685	93	12
2	2	5	3094	814	77	43
2	2	5	2779	884	98	68
2	2	5	2662	770	97	38
2	2	10	2776	988	97	67
2	2	10	2836	807	95	25
2	2	10	2844	763	83	13
2	2	10	2889	1068	97	67
2	2	10	2781	1118	100	87
2	2	10	2917	1033	67	78
2	2	10	2394	672	77	27
3	1	5	3405	1444	95	95
3	1	5	2638	1152	100	100
3	1	5	2614	1262	90	93
3	1	5	2755	1204	87	83
3	1	5	2614	1179	92	80
3	1	5	2750	1237	95	92
3	1	5	3432	1237	75	57
3	1	10	3196	1263	55	28
3	1	10	3342	1263	77	88
3	1	10	3078	1425	90	93
3	1	10	3122	1323	83	58
3	1	10	2832	1222	92	85
3	1	10	2888	1420	75	87
3	1	10	2650	1427	98	100
3	2	5	2634	1330	98	93
3	2	5	2785	1257	75	73
3	2	5	2985	1299	92	82
3	2	5	3221	1448	78	90
3	2	5	2912	1014	60	73
3	2	5	2634	1247	98	90
3	2	5	2593	1215	98	98
3	2	10	3136	1436	73	58
3	2	10	3117	1484	77	97
3	2	10	2574	1325	67	80
3	2	10	2936	1462	92	97
3	2	10	2926	1487	90	100
3	2	10	2601	1138	97	95
3	2	10	2659	1302	93	80
4	1	5	2863	1442	87	95
4	1	5	3501	1390	93	95
4	1	5	2736	1295	92	88
4	1	5	2284	1114	93	98
4	1	5	3136	1311	92	83
4	1	5	2662	876	78	70

Table A1. Continued

4	1	5	2756	1187	100	67
4	1	10	2939	1363	100	100
4	1	10	2700	1330	98	100
4	1	10	2762	1131	100	100
4	1	10	3152	1411	100	80
4	1	10	3168	1512	93	100
4	1	10	2790	1293	87	100
4	1	10	2965	1293	78	93
4	2	5	2816	1322	98	93
4	2	5	3028	1038	95	87
4	2	5	3379	1438	82	72
4	2	5	3011	1308	95	98
4	2	5	3059	1363	44	90
4	2	5	3256	1164	73	17
4	2	5	2584	1251	92	97
4	2	10	2805	1258	87	98
4	2	10	2866	1383	100	98
4	2	10	2930	1431	88	100
4	2	10	2536	1507	88	100
4	2	10	3003	1480	95	83
4	2	10	2736	1174	70	100
4	2	10	2919	1406	95	100
5	1	5	3279	943	78	25
5	1	5	3178	595	67	10
5	1	5	3605	717	93	43
5	1	5	2936	695	65	10
5	1	5	2726	644	78	12
5	1	5	2881	748	60	15
5	1	5	2755	422	80	13
5	1	10	2694	821	93	12
5	1	10	2889	1460	92	77
5	1	10	3028	1423	95	88
5	1	10	2819	659	83	17
5	1	10	2693	1008	100	32
5	1	10	3174	624	65	12
5	1	10	3110	1487	67	100
5	2	5	2971	660	80	13
5	2	5	2717	800	100	20
5	2	5	2630	997	100	10
5	2	5	3318	352	58	0
5	2	5	2907	617	40	10
5	2	5	3031	962	73	33
5	2	5	2689	528	98	3
5	2	10	2348	1330	95	93
5	2	10	2734	762	78	25
5	2	10	2624	1123	90	70
5	2	10	2741	1025	77	38
5	2	10	3151	661	75	58
5	2	10	2397	1191	93	92
5	2	10	2483	1211	98	87

;

Table A1. Continued

```
PROC PRINT;
PROC MEANS N MEAN VAR STD CV DATA=HMR1;
 BY T S C;
 VAR SHEAR_D SHEAR_W WF_D WF_W;
 OUTPUT OUT=HMR2 N=N MEAN=MEAN VAR=VAR STD=STD CV=COV;
PROC GLM DATA=HMR1;
 CLASS T S C;
 MODEL SHEAR_D SHEAR_W WF_D WF_W=T S C T*S T*C S*C T*S*C;
 CONTRAST '5 VS OTH' T 1 1 1 1 -4;
 CONTRAST '1 VS 2-4' T 3 -1 -1 -1 0;
 CONTRAST '2 VS 3+4' T 0 2 -1 -1 0;
 CONTRAST '3 VS 4'   T 0 0 1 -1 0;
 OUTPUT OUT=HMR3 PREDICTED=P1-P4 RESIDUAL=RES1-RES4;
 MEANS T S C/DUNCAN;
 MEANS T S C T*S T*C S*C T*S*C;
PROC UNIVARIATE PLOT NORMAL;
 VAR RES1 RES2 RES3 RES4;
 DATA HMR3;
 SET HMR3;
 RES1AB=ABS(RES1);
 RES2AB=ABS(RES2);
 RES3AB=ABS(RES3);
 RES4AB=ABS(RES4);
PROC PRINT;
PROC GLM;
 CLASS T S C;
 MODEL RES1AB RES2AB RES3AB RES4AB=T S C T*S T*C S*C T*S*C;
```

Table A2. List of Treatments, Shear Strength Dry and Wet (psi, MPa) and Wood Failure Dry and Wet (%)

OBS	T	S	C	SHE_D	SHE_W	WF_D	WF_W	SHEAR_D	SHEAR_W
1	1	1	5	2789	515	80	7	19.2296	3.55082
2	1	1	5	2282	429	97	0	15.7339	2.95787
3	1	1	5	3113	471	58	3	21.4635	3.24745
4	1	1	5	2752	614	68	17	18.9745	4.23341
5	1	1	5	2484	794	90	38	17.1267	5.47447
6	1	1	5	2668	400	63	0	18.3953	2.75792
7	1	1	5	2630	595	37	0	18.1333	4.10241
8	1	1	10	2721	702	92	37	18.7608	4.84015
9	1	1	10	2864	599	28	53	19.7467	4.12999
10	1	1	10	2702	627	92	13	18.6297	4.32304
11	1	1	10	2500	493	53	15	17.2370	3.39914
12	1	1	10	2638	625	73	10	18.1885	4.30925
13	1	1	10	3118	815	77	47	21.4980	5.61926
14	1	1	10	1929	605	43	12	13.3001	4.17135
15	1	2	5	3031	575	77	2	20.8981	3.96451
16	1	2	5	2528	727	100	10	17.4301	5.01252
17	1	2	5	2653	592	77	3	18.2919	4.08172
18	1	2	5	2608	849	65	35	17.9816	5.85369
19	1	2	5	3258	513	95	8	22.4633	3.53703
20	1	2	5	2813	602	82	13	19.3951	4.15067
21	1	2	5	1406	517	27	7	9.6941	3.56461
22	1	2	10	3128	239	47	0	21.5669	1.64786
23	1	2	10	2056	634	25	20	14.1757	4.37130
24	1	2	10	2854	523	38	0	19.6778	3.60598
25	1	2	10	2377	549	70	13	16.3889	3.78525
26	1	2	10	2867	617	63	3	19.7674	4.25409
27	1	2	10	1395	356	32	0	9.6182	2.45455
28	1	2	10	3238	679	70	8	22.3254	4.68157
29	2	1	5	3169	826	70	60	21.8496	5.69510
30	2	1	5	3169	891	100	67	21.8496	6.14327
31	2	1	5	2630	1105	98	75	18.1333	7.61875
32	2	1	5	3203	978	57	28	22.0840	6.74311
33	2	1	5	3259	1062	78	60	22.4702	7.32228
34	2	1	5	3349	1020	53	43	23.0907	7.03270
35	2	1	5	2539	1093	97	63	17.5059	7.53602
36	2	1	10	2595	914	75	32	17.8920	6.30185
37	2	1	10	3663	1237	95	47	25.2557	8.52887
38	2	1	10	2794	1277	62	48	19.2641	8.80466
39	2	1	10	2779	1149	88	77	19.1606	7.92213
40	2	1	10	2697	1252	80	65	18.5953	8.63229
41	2	1	10	2932	899	83	53	20.2156	6.19843
42	2	1	10	2208	757	30	18	15.2237	5.21936
43	2	2	5	3115	604	87	23	21.4773	4.16446
44	2	2	5	3027	940	87	68	20.8706	6.48111
45	2	2	5	2845	811	83	7	19.6157	5.59168
46	2	2	5	2818	685	93	12	19.4295	4.72294
47	2	2	5	3094	814	77	43	21.3325	5.61237
48	2	2	5	2779	884	98	68	19.1606	6.09500
49	2	2	5	2662	770	97	38	18.3540	5.30900

Table A2. Continued

50	2	2	10	2776	988	97	67	19.1400	6.81206
51	2	2	10	2836	807	95	25	19.5537	5.56410
52	2	2	10	2844	763	83	13	19.6088	5.26073
53	2	2	10	2889	1068	97	67	19.9191	7.36365
54	2	2	10	2781	1118	100	87	19.1744	7.70839
55	2	2	10	2917	1033	67	78	20.1121	7.12233
56	2	2	10	2394	672	77	27	16.5062	4.6333
57	3	1	5	3405	1444	95	95	23.4768	9.9561
58	3	1	5	2638	1152	100	100	18.1885	7.9428
59	3	1	5	2614	1262	90	93	18.0230	8.7012
60	3	1	5	2755	1204	87	83	18.9952	8.3013
61	3	1	5	2614	1179	92	80	18.0230	8.1290
62	3	1	5	2750	1237	95	92	18.9607	8.5289
63	3	1	5	3432	1237	75	57	23.6630	8.5289
64	3	1	10	3196	1263	55	28	22.0358	8.7081
65	3	1	10	3342	1263	77	88	23.0424	8.7081
66	3	1	10	3078	1425	90	93	21.2222	9.8251
67	3	1	10	3122	1323	83	58	21.5256	9.1218
68	3	1	10	2832	1222	92	85	19.5261	8.4254
69	3	1	10	2888	1420	75	87	19.9122	9.7906
70	3	1	10	2650	1427	98	100	18.2712	9.8389
71	3	2	5	2634	1330	98	93	18.1609	9.1701
72	3	2	5	2785	1257	75	73	19.2020	8.6668
73	3	2	5	2985	1299	92	82	20.5810	8.9563
74	3	2	5	3221	1448	78	90	22.2082	9.9837
75	3	2	5	2912	1014	60	73	20.0777	6.9913
76	3	2	5	2634	1247	98	90	18.1609	8.5978
77	3	2	5	2593	1215	98	98	17.8782	8.3772
78	3	2	10	3136	1436	73	58	21.6221	9.9009
79	3	2	10	3117	1484	77	97	21.4911	10.2319
80	3	2	10	2574	1325	67	80	17.7472	9.1356
81	3	2	10	2936	1462	92	97	20.2431	10.0802
82	3	2	10	2926	1487	90	100	20.1742	10.2526
83	3	2	10	2601	1138	97	95	17.9334	7.8463
84	3	2	10	2659	1302	93	80	18.3333	8.9770
85	4	1	5	2863	1442	87	95	19.7398	9.9423
86	4	1	5	3501	1390	93	95	24.1387	9.5838
87	4	1	5	2736	1295	92	88	18.8642	8.9288
88	4	1	5	2284	1114	93	98	15.7477	7.6808
89	4	1	5	3136	1311	92	83	21.6221	9.0391
90	4	1	5	2662	876	78	70	18.3540	6.0398
91	4	1	5	2756	1187	100	67	19.0021	8.1841
92	4	1	10	2939	1363	100	100	20.2638	9.3976
93	4	1	10	2700	1330	98	100	18.6160	9.1701
94	4	1	10	2762	1131	100	100	19.0434	7.7980
95	4	1	10	3152	1411	100	80	21.7324	9.7286
96	4	1	10	3168	1512	93	100	21.8427	10.4249
97	4	1	10	2790	1293	87	100	19.2365	8.9150
98	4	1	10	2965	1293	78	93	20.4431	8.9150
99	4	2	5	2816	1322	98	93	19.4158	9.1149

Table A3. Means of Treatment Groups: Shear Strength Dry and Wet (MPa) and Wood Failure Dry and Wet (%)

T=1 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	18.4366952	3.1990560	1.7885905	9.7012533
SHEAR_W	7	3.7606209	0.8724676	0.9340597	24.8379120
WF_D	7	70.4285714	418.9523810	20.4683263	29.0625323
WF_W	7	9.2857143	197.9047619	14.0678627	151.5000602

T=1 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	18.1943922	6.4507912	2.5398408	13.9594703
SHEAR_W	7	4.3988824	0.4702327	0.6857351	15.5888493
WF_D	7	65.4285714	610.2857143	24.7039615	37.7571464
WF_W	7	26.7142857	338.2380952	18.3912505	68.8442532

T=1 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	18.0220222	16.6102101	4.0755625	22.6143465
SHEAR_W	7	4.3092500	0.7044062	0.8392891	19.4764542
WF_D	7	74.7142857	580.9047619	24.1019659	32.2588454
WF_W	7	11.1428571	125.1428571	11.1867268	100.3937023

T=1 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	17.6457631	20.6610771	4.5454458	25.7594172
SHEAR_W	7	3.5429422	1.2211698	1.1050655	31.1906163
WF_D	7	49.2857143	344.5714286	18.5626353	37.6633180
WF_W	7	6.2857143	60.9047619	7.8041503	124.1569366

T=2 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.9976209	4.9296210	2.2202750	10.5739359
SHEAR_W	7	6.8701757	0.5266425	0.7257014	10.5630688
WF_D	7	79.0000000	394.6666667	19.8662192	25.1471130
WF_W	7	56.5714286	252.2857143	15.8835045	28.0769018

Table A3. Continued

T=2 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.3724181	9.2311980	3.0382887	15.6835799
SHEAR_W	7	7.3725111	2.0730284	1.4398015	19.5293229
WF_D	7	73.2857143	471.9047619	21.7233690	29.6420240
WF_W	7	48.5714286	384.9523810	19.6202034	40.3945364

T=2 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.0343189	1.4324502	1.1968501	5.9739996
SHEAR_W	7	5.4252226	0.6204129	0.7876629	14.5185363
WF_D	7	88.8571429	58.1428571	7.6251464	8.5813544
WF_W	7	37.0000000	613.3333333	24.7655675	66.9339662

T=2 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.1448897	1.4801786	1.2166259	6.3548338
SHEAR_W	7	6.3520807	1.4056386	1.1855963	18.6646923
WF_D	7	88.0000000	157.0000000	12.5299641	14.2385956
WF_W	7	52.0000000	871.0000000	29.5127091	56.7552099

T=3 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.9043026	6.4382728	2.5373752	12.7478727
SHEAR_W	7	8.5840260	0.4334222	0.6583481	7.6694561
WF_D	7	90.5714286	64.2857143	8.0178373	8.8525017
WF_W	7	85.7142857	207.9047619	14.4189029	16.8220534

T=3 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.7907769	2.6775906	1.6363345	7.8704827
SHEAR_W	7	9.2025881	0.3729332	0.6106826	6.6359870
WF_D	7	81.4285714	203.6190476	14.2695146	17.5239653
WF_W	7	77.0000000	638.6666667	25.2718552	32.8205912

Table A3. Continued

T=3 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.4669753	2.5223306	1.5881847	8.1583537
SHEAR_W	7	8.6775983	0.8277182	0.9097902	10.4843548
WF_D	7	85.5714286	221.2857143	14.8756753	17.3839277
WF_W	7	85.5714286	96.2857143	9.8125284	11.4670616

T=3 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.6491950	2.7010836	1.6434974	8.3641969
SHEAR_W	7	9.4892147	0.7899389	0.8887850	9.3662655
WF_D	7	84.1428571	134.8095238	11.6107504	13.7988544
WF_W	7	86.7142857	228.5714286	15.1185789	17.4349345

T=4 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.6383603	6.9982464	2.6454199	13.4706760
SHEAR_W	7	8.4855289	1.7584994	1.3260842	15.6275966
WF_D	7	90.7142857	45.9047619	6.7753053	7.4688405
WF_W	7	85.1428571	155.1428571	12.4556356	14.6291022

T=4 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.1682750	1.6463521	1.2831025	6.3619844
SHEAR_W	7	9.1927383	0.6579092	0.8111160	8.8234432
WF_D	7	93.7142857	71.5714286	8.4599899	9.0274282
WF_W	7	96.1428571	57.4761905	7.5813053	7.8854587

T=4 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.8154012	3.3114206	1.8197309	8.7422332
SHEAR_W	7	8.7504862	0.8433040	0.9183158	10.4944549
WF_D	7	82.7142857	369.2380952	19.2155691	23.2312580
WF_W	7	79.1428571	826.4761905	28.7484989	36.3248181

Table A3. Continued

T=4 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.4975094	1.1489275	1.0718803	5.4975244
SHEAR_W	7	9.4941396	0.6867061	0.8286773	8.7283036
WF_D	7	89.0000000	93.3333333	9.6609178	10.8549639
WF_W	7	97.0000000	39.0000000	6.2449980	6.4381423

T=5 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	21.0389897	4.8361766	2.1991309	10.4526448
SHEAR_W	7	4.6924039	1.1921782	1.0918692	23.2688655
WF_D	7	74.4285714	125.6190476	11.2079903	15.0587202
WF_W	7	18.2857143	145.2380952	12.0514769	65.9065142

T=5 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	20.1003119	1.7897478	1.3378146	6.6556906
SHEAR_W	7	7.3695562	7.0061174	2.6469071	35.9167777
WF_D	7	85.0000000	194.3333333	13.9403491	16.4004107
WF_W	7	48.2857143	1492.24	38.6294977	80.0019184

T=5 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	19.9584761	2.7547588	1.6597466	8.3159987
SHEAR_W	7	4.8421195	2.5828604	1.6071280	33.1905893
WF_D	7	78.4285714	539.9523810	23.2368755	29.6280744
WF_W	7	12.7142857	122.5714286	11.0711982	87.0768394

T=5 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
SHEAR_D	7	18.2003021	3.5604215	1.8869079	10.3674539
SHEAR_W	7	7.1932463	2.8848235	1.6984768	23.6121042
WF_D	7	86.5714286	92.2857143	9.6065454	11.0966696
WF_W	7	66.1428571	731.8095238	27.0519782	40.8993191

Table A4. Normality Test on the Residuals of the Variable Shear Strength Dry (MPa)

Univariate Procedure

Variable=RES1

Moments

N	140	Sum Wgts	140
Mean	0	Sum	0
Std Dev	2.122642	Variance	4.505608
Skewness	-0.50264	Kurtosis	2.467445
USS	626.2795	CSS	626.2795
CV	.	Std Mean	0.179396
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	140	Num > 0	71
M(Sign)	1	Pr>=|M|	0.9327
Sgn Rank	28	Pr>=|S|	0.9538
W:Normal	0.966355	Pr<W	0.0260

Quantiles(Def=5)

100% Max	5.883234	99%	4.679599
75% Q3	1.160789	95%	3.665571
50% Med	0.045801	90%	2.611652
25% Q1	-1.29524	10%	-2.02806
0% Min	-8.32793	5%	-3.23465
		1%	-8.02752
Range	14.21117		
Q3-Q1	2.456026		
Mode	-1.8813		

Extremes

Lowest	Obs	Highest	Obs
-8.32793(	21)	3.921171(	22)
-8.02752(	27)	4.441236(	19)
-4.89432(	14)	4.500334(	86)
-4.1487(	42)	4.679599(	28)
-3.89064(	88)	5.883234(	37)

Table A5. Boxplot of the Residuals of the Variable Shear Strength Dry (MPa)

```
                         Univariate Procedure

Variable=RES1

     Stem Leaf                                 #             Boxplot
        5 9                                    1                0
        4 457                                  3                |
        3 0356889                              7                |
        2 0001135799                          10                |
        1 01122334456666788                   17             +-----+
        0 011113333444555566667777888889999   33             *--+--*
       -0 99999888766664332222111 0000        26             |     |
       -1 999877776655544333333322110         27             +-----+
       -2 97652000                             8                |
       -3 9550                                 4                |
       -4 91                                   2                |
       -5
       -6
       -7
       -8 30                                   2                0
          ----+----+----+----+----+----+---
```

Table A6. Normality Test on the Residuals of the Variable Shear Strength Wet (MPa)

Univariate Procedure

Variable=RES2

Moments

N	140	Sum Wgts	140
Mean	0	Sum	0
Std Dev	1.098011	Variance	1.205629
Skewness	-0.24137	Kurtosis	0.358047
USS	167.5825	CSS	167.5825
CV	.	Std Mean	0.092799
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	140	Num > 0	70
M(Sign)	0	Pr>=|M|	1.0000
Sgn Rank	153	Pr>=|S|	0.7515
W:Normal	0.98204	Pr<W	0.5537

Quantiles(Def=5)

100% Max	2.883011	99%	2.696852
75% Q3	0.671751	95%	1.752264
50% Med	0.015267	90%	1.282925
25% Q1	-0.67175	10%	-1.49666
0% Min	-3.0672	5%	-1.91725
		1%	-2.82588
Range	5.950212		
Q3-Q1	1.343501		
Mode	-0.49446		

Extremes

Lowest	Obs	Highest	Obs
-3.0672(	125)	1.976838(	134)
-2.82588(	123)	2.031996(	129)
-2.63578(	138)	2.441744(	122)
-2.44568(	90)	2.696852(	121)
-2.41515(	130)	2.883011(	126)

Table A7. Boxplot of the Residuals of the Variable Shear Strength Wet (MPa)

```
                        Univariate Procedure

Variable=RES2

        Stem Leaf                          #             Boxplot
           2 79                            2                0
           2 004                           3                |
           1 55788                         5                |
           1 001112222233444              15                |
           0 55555555666666777777778889   26             +-----+
           0 0111222222333344444          19             *--+--*
          -0 443333333332222111111111100  27             |     |
          -0 888888777766655555           18             +-----+
          -1 44322211100                  11                |
          -1 99877766                      8                |
          -2 442                           3                |
          -2 86                            2                0
          -3 1                             1                0
             ----+----+----+----+----+--
```

Table A8. Normality Test on the Residuals of the Variable Wood Failure Dry (%)

Univariate Procedure

Variable=RES3

Moments

N	140	Sum Wgts	140
Mean	0	Sum	0
Std Dev	14.97144	Variance	224.1439
Skewness	-0.74523	Kurtosis	0.589853
USS	31156	CSS	31156
CV	.	Std Mean	1.265317
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	140	Num > 0	78
M(Sign)	8	Pr>=|M|	0.2047
Sgn Rank	388	Pr>=|S|	0.4216
W:Normal	0.950448	Pr<W	0.0002

Quantiles(Def=5)

100% Max	26.57143	99%	26.57143
75% Q3	9.5	95%	21.28571
50% Med	2.285714	90%	18.78571
25% Q1	-9.5	10%	-20.2143
0% Min	-47.7143	5%	-26.2143
		1%	-43.2857
Range	74.28571		
Q3-Q1	19		
Mode	6.285714		

Extremes

Lowest	Obs	Highest	Obs
-47.7143(	21)	21.71429(	37)
-43.2857(	42)	25.28571(	16)
-38.7143(	103)	26.57143(	2)
-38.4286(	131)	26.57143(	8)
-37.4286(	9)	26.57143(	10)

Table A9. Boxplot of the Residuals of the Variable Wood Failure Dry (%)

```
                          Univariate Procedure

Variable=RES3

         Stem Leaf                              #             Boxplot
            2 5777                              4                |
            2 000111222                         9                |
            1 5557899                           7                |
            1 000111222222234                  15             +-----+
            0 66666666677778888899999999       26             |     |
            0 11122222223444444                17             *--+--*
           -0 444222222111111                  15             |     |
           -0 999877776655                     12             |     |
           -1 43222211111000                   14             +-----+
           -1 987766                            6                |
           -2 422100                            6                |
           -2 666                               3                |
           -3 3                                 1                |
           -3 987                               3                0
           -4 3                                 1                0
           -4 8                                 1                0
              ----+----+----+----+----+-
          Multiply Stem.Leaf by 10**+1
```

Table A10. Normality Test on the Residuals of the Variable Wood Failure Wet (%)

Univariate Procedure

Variable=RES4

Moments

N	140	Sum Wgts	140
Mean	0	Sum	0
Std Dev	18.09465	Variance	327.4162
Skewness	-0.36901	Kurtosis	0.872717
USS	45510.86	CSS	45510.86
CV	.	Std Mean	1.529277
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	140	Num > 0	75
M(Sign)	5	Pr>=|M|	0.4470
Sgn Rank	219	Pr>=|S|	0.6504
W:Normal	0.985299	Pr<W	0.7520

Quantiles(Def=5)

100% Max	51.71429	99%	39.71429
75% Q3	10.28571	95%	28.57143
50% Med	1.785714	90%	23.42857
25% Q1	-9.28571	10%	-26
0% Min	-62.1429	5%	-30.9286
		1%	-49
Range	113.8571		
Q3-Q1	19.57143		
Mode	3.857143		

Extremes

Lowest	Obs	Highest	Obs
-62.1429(	104)	31(	44)
-49(	64)	31(	48)
-41.1429(	135)	35(	54)
-39(	52)	39.71429(	122)
-36.2857(	125)	51.71429(	126)

Table A11. Boxplot of the Residuals of the Variable Wood Failure Wet (%)

```
                    Univariate Procedure

Variable=RES4

           Stem Leaf                     #             Boxplot
              5 2                        1                0
              4
              4 0                        1                0
              3 5                        1                |
              3 11                       2                |
              2 56667899                 8                |
              2 00134                    5                |
              1 5566889                  7                |
              1 000000011233444         15             +-----+
              0 6667777788889           13             |     |
              0 0111223333333444444444  22             *--+--*
             -0 44333333322211          14             |     |
             -0 999988887776666665      18             +-----+
             -1 444433320                9                |
             -1 98776655                 8                |
             -2                                           |
             -2 9998755                  7                |
             -3 110                      3                |
             -3 966                      3                0
             -4 1                        1                0
             -4 9                        1                0
             -5
             -5
             -6 2                        1                0
                ----+----+----+----+--
            Multiply Stem.Leaf by 10**+1
```

Table A12. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Shear Strength Dry (MPa)

General Linear Models Procedure

Dependent Variable: RES1AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	59.006363	3.105598	1.66	0.0523
Error	120	224.175015	1.868125		
Corrected Total	139	283.181378			

R-Square	C.V.	Root MSE	RES1AB Mean
0.208370	87.30877	1.3668	1.5655

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	19.017194	4.754298	2.54	0.0430
S	1	0.083826	0.083826	0.04	0.8326
C	1	0.468006	0.468006	0.25	0.6176
T*S	4	27.822839	6.955710	3.72	0.0068
T*C	4	7.875468	1.968867	1.05	0.3825
S*C	1	1.926632	1.926632	1.03	0.3119
T*S*C	4	1.812397	0.453099	0.24	0.9137

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	19.017194	4.754298	2.54	0.0430
S	1	0.083826	0.083826	0.04	0.8326
C	1	0.468006	0.468006	0.25	0.6176
T*S	4	27.822839	6.955710	3.72	0.0068
T*C	4	7.875468	1.968867	1.05	0.3825
S*C	1	1.926632	1.926632	1.03	0.3119
T*S*C	4	1.812397	0.453099	0.24	0.9137

Table A13. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Shear Strength Wet (MPa)

General Linear Models Procedure

Dependent Variable: RES2AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	25.223581	1.327557	3.86	0.0001
Error	120	41.275318	0.343961		
Corrected Total	139	66.498899			

R-Square	C.V.	Root MSE	RES2AB Mean
0.379308	69.02054	0.5865	0.8497

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	12.578436	3.144609	9.14	0.0001
S	1	0.016864	0.016864	0.05	0.8251
C	1	1.989533	1.989533	5.78	0.0177
T*S	4	0.847202	0.211801	0.62	0.6521
T*C	4	5.207590	1.301898	3.79	0.0062
S*C	1	0.258873	0.258873	0.75	0.3874
T*S*C	4	4.325083	1.081271	3.14	0.0169

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	12.578436	3.144609	9.14	0.0001
S	1	0.016864	0.016864	0.05	0.8251
C	1	1.989533	1.989533	5.78	0.0177
T*S	4	0.847202	0.211801	0.62	0.6521
T*C	4	5.207590	1.301898	3.79	0.0062
S*C	1	0.258873	0.258873	0.75	0.3874
T*S*C	4	4.325083	1.081271	3.14	0.0169

Table A14. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Wood Failure Dry (%)

General Linear Models Procedure

Dependent Variable: RES3AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	2925.4408	153.9706	2.10	0.0084
Error	120	8797.5977	73.3133		
Corrected Total	139	11723.0385			

R-Square	C.V.	Root MSE	RES3AB Mean
0.249546	72.67515	8.5623	11.782

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	1345.6012	336.4003	4.59	0.0018
S	1	1.7638	1.7638	0.02	0.8770
C	1	2.6175	2.6175	0.04	0.8504
T*S	4	746.3265	186.5816	2.54	0.0430
T*C	4	209.3563	52.3391	0.71	0.5840
S*C	1	296.4251	296.4251	4.04	0.0466
T*S*C	4	323.3504	80.8376	1.10	0.3586

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	1345.6012	336.4003	4.59	0.0018
S	1	1.7638	1.7638	0.02	0.8770
C	1	2.6175	2.6175	0.04	0.8504
T*S	4	746.3265	186.5816	2.54	0.0430
T*C	4	209.3563	52.3391	0.71	0.5840
S*C	1	296.4251	296.4251	4.04	0.0466
T*S*C	4	323.3504	80.8376	1.10	0.3586

Table A15. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Wood Failure Wet (%)

General Linear Models Procedure

Dependent Variable: RES4AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	7982.6845	420.1413	4.58	0.0001
Error	120	11008.3265	91.7361		
Corrected Total	139	18991.0111			

R-Square	C.V.	Root MSE	RES4AB Mean
0.420340	69.59027	9.5779	13.763

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	1927.7574	481.9394	5.25	0.0006
S	1	23.7924	23.7924	0.26	0.6115
C	1	705.5394	705.5394	7.69	0.0064
T*S	4	1533.3504	383.3376	4.18	0.0033
T*C	4	3197.2711	799.3178	8.71	0.0001
S*C	1	314.1434	314.1434	3.42	0.0667
T*S*C	4	280.8303	70.2076	0.77	0.5498

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	1927.7574	481.9394	5.25	0.0006
S	1	23.7924	23.7924	0.26	0.6115
C	1	705.5394	705.5394	7.69	0.0064
T*S	4	1533.3504	383.3376	4.18	0.0033
T*C	4	3197.2711	799.3178	8.71	0.0001
S*C	1	314.1434	314.1434	3.42	0.0667
T*S*C	4	280.8303	70.2076	0.77	0.5498

Appendix B.

Statistical Data of the Experiment

to Reduce the HMR Drying Time

(Transformed Datasets with Dropped Data)

Table B1. SAS File

```
/*DRYING OF N-HMR - EPOXY RESIN (FPL-1) ON HARD MAPLE
5x2x2 FACTORIAL W/ 7 REPS, CARRIED OUT: FALL 2002;
FILENAME: DRYHMR3 SAS; 1=5MIN, 2=10MIN, 3=15MIN, 4=20MIN, 5=24HOURS;
LOG AND ARCSIN TRANSFORMED; DROPPED DATA*/
OPTIONS LINESIZE=72;
DATA HMR1;
INPUT T S C SHE_D SHE_W WF_D WF_W;
LOGSH_D=LOG10(SHE_D*0.0068948);
LOGSH_W=LOG10(10+SHE_W*0.0068948);
ARWF_D=ARSIN(SQRT(WF_D/100));
ARWF_W=ARSIN(SQRT(WF_W/100));
CARDS;
1 1  5 2789  515  80   7
1 1  5 2282  429  97   0
1 1  5 3113  471  58   3
1 1  5 2752  614  68  17
1 1  5 2484  794  90  38
1 1  5 2668  400  63   0
1 1  5 2630  595  37   0
1 1 10 2721  702  92  37
1 1 10 2864  599  28  53
1 1 10 2702  627  92  13
1 1 10 2500  493  53  15
1 1 10 2638  625  73  10
1 1 10 3118  815  77  47
1 1 10 1929  605  43  12
1 2  5 3031  575  77   2
1 2  5 2528  727 100  10
1 2  5 2653  592  77   3
1 2  5 2608  849  65  35
1 2  5 3258  513  95   8
1 2  5 2813  602  82  13
1 2  5    .  517  27   7
1 2 10 3128    .  47   0
1 2 10 2056  634  25  20
1 2 10 2854  523  38   0
1 2 10 2377  549  70  13
1 2 10 2867  617  63   3
1 2 10    .  356  32   0
1 2 10 3238  679  70   8
2 1  5 3169  826  70  60
2 1  5 3169  891 100  67
2 1  5 2630 1105  98  75
2 1  5 3203  978  57  28
2 1  5 3259 1062  78  60
2 1  5 3349 1020  53  43
2 1  5 2539 1093  97  63
2 1 10 2595  914  75  32
2 1 10 3663 1237  95  47
2 1 10 2794 1277  62  48
2 1 10 2779 1149  88  77
2 1 10 2697 1252  80  65
```

Table B1. Continued

2	1	10	2932	899	83	53
2	1	10	2208	757	30	18
2	2	5	3115	604	87	23
2	2	5	3027	940	87	68
2	2	5	2845	811	83	7
2	2	5	2818	685	93	12
2	2	5	3094	814	77	43
2	2	5	2779	884	98	68
2	2	5	2662	770	97	38
2	2	10	2776	988	97	67
2	2	10	2836	807	95	25
2	2	10	2844	763	83	13
2	2	10	2889	1068	97	67
2	2	10	2781	1118	100	87
2	2	10	2917	1033	67	78
2	2	10	2394	672	77	27
3	1	5	3405	1444	95	95
3	1	5	2638	1152	100	100
3	1	5	2614	1262	90	93
3	1	5	2755	1204	87	83
3	1	5	2614	1179	92	80
3	1	5	2750	1237	95	92
3	1	5	3432	1237	75	57
3	1	10	3196	1263	55	28
3	1	10	3342	1263	77	88
3	1	10	3078	1425	90	93
3	1	10	3122	1323	83	58
3	1	10	2832	1222	92	85
3	1	10	2888	1420	75	87
3	1	10	2650	1427	98	100
3	2	5	2634	1330	98	93
3	2	5	2785	1257	75	73
3	2	5	2985	1299	92	82
3	2	5	3221	1448	78	90
3	2	5	2912	1014	60	73
3	2	5	2634	1247	98	90
3	2	5	2593	1215	98	98
3	2	10	3136	1436	73	58
3	2	10	3117	1484	77	97
3	2	10	2574	1325	67	80
3	2	10	2936	1462	92	97
3	2	10	2926	1487	90	100
3	2	10	2601	1138	97	95
3	2	10	2659	1302	93	80
4	1	5	2863	1442	87	95
4	1	5	3501	1390	93	95
4	1	5	2736	1295	92	88
4	1	5	2284	1114	93	98
4	1	5	3136	1311	92	83
4	1	5	2662	876	78	70
4	1	5	2756	1187	100	67

Table B1. Continued

4	1	10	2939	1363	100	100
4	1	10	2700	1330	98	100
4	1	10	2762	1131	100	100
4	1	10	3152	1411	100	80
4	1	10	3168	1512	93	100
4	1	10	2790	1293	87	100
4	1	10	2965	1293	78	93
4	2	5	2816	1322	98	93
4	2	5	3028	1038	95	87
4	2	5	3379	1438	82	72
4	2	5	3011	1308	95	98
4	2	5	3059	1363	44	90
4	2	5	3256	1164	73	.
4	2	5	2584	1251	92	97
4	2	10	2805	1258	87	98
4	2	10	2866	1383	100	98
4	2	10	2930	1431	88	100
4	2	10	2536	1507	88	100
4	2	10	3003	1480	95	83
4	2	10	2736	1174	70	100
4	2	10	2919	1406	95	100
5	1	5	3279	943	78	25
5	1	5	3178	595	67	10
5	1	5	3605	717	93	43
5	1	5	2936	695	65	10
5	1	5	2726	644	78	12
5	1	5	2881	748	60	15
5	1	5	2755	422	80	13
5	1	10	2694	821	93	12
5	1	10	2889	1460	92	77
5	1	10	3028	1423	95	88
5	1	10	2819	659	83	17
5	1	10	2693	1008	100	32
5	1	10	3174	624	65	12
5	1	10	3110	1487	67	.
5	2	5	2971	660	80	13
5	2	5	2717	800	100	20
5	2	5	2630	997	100	10
5	2	5	3318	.	58	0
5	2	5	2907	617	40	10
5	2	5	3031	962	73	33
5	2	5	2689	528	98	3
5	2	10	2348	1330	95	93
5	2	10	2734	762	78	25
5	2	10	2624	1123	90	70
5	2	10	2741	1025	77	38
5	2	10	3151	661	75	58
5	2	10	2397	1191	93	92
5	2	10	2483	1211	98	87

;

Table B1. Continued

```
PROC PRINT;
PROC MEANS N MEAN VAR STD CV DATA=HMR1;
 BY T S C;
 VAR LOGSH_D LOGSH_W ARWF_D ARWF_W;
 OUTPUT OUT=HMR2 N=N MEAN=MEAN VAR=VAR STD=STD CV=COV;
PROC GLM DATA=HMR1;
 CLASS T S C;
 MODEL LOGSH_D LOGSH_W ARWF_D ARWF_W=T S C T*S T*C S*C T*S*C;
 CONTRAST '5 VS OTH' T 1 1 1 1 -4;
 CONTRAST '1 VS 2-4' T 3 -1 -1 -1 0;
 CONTRAST '2 VS 3+4' T 0 2 -1 -1 0;
 CONTRAST '3 VS 4  ' T 0 0 1 -1 0;
 OUTPUT OUT=HMR3 PREDICTED=P1-P4 RESIDUAL=RES1-RES4;
 MEANS T S C/DUNCAN;
 MEANS T S C T*S T*C S*C T*S*C;
PROC UNIVARIATE PLOT NORMAL;
 VAR RES1 RES2 RES3 RES4;
 DATA HMR3;
 SET HMR3;
 RES1AB=ABS(RES1);
 RES2AB=ABS(RES2);
 RES3AB=ABS(RES3);
 RES4AB=ABS(RES4);
PROC PRINT;
PROC GLM;
 CLASS T S C;
 MODEL RES1AB RES2AB RES3AB RES4AB=T S C T*S T*C S*C T*S*C;
```

Table B2. List of Treatments, Shear Strength Dry and Wet (psi, MPa) and Wood Failure Dry and Wet (%)

OBS	T	S	C	SHE_D	SHE_W	WF_D	WF_W	LOGSH_D	LOGSH_W	ARWF_D	ARWF_W
1	1	1	5	2789	515	80	7	1.28397	1.13197	1.10715	0.26776
2	1	1	5	2282	429	97	0	1.19684	1.11253	1.39671	0.00000
3	1	1	5	3113	471	58	3	1.33170	1.12213	0.86574	0.17408
4	1	1	5	2752	614	68	17	1.27817	1.15331	0.96953	0.42499
5	1	1	5	2484	794	90	38	1.23367	1.18962	1.24905	0.66422
6	1	1	5	2668	400	63	0	1.26471	1.10578	0.91691	0.00000
7	1	1	5	2630	595	37	0	1.25848	1.14929	0.65389	0.00000
8	1	1	10	2721	702	92	37	1.27325	1.17144	1.28404	0.65389
9	1	1	10	2864	599	28	53	1.29549	1.15014	0.55760	0.81542
10	1	1	10	2702	627	92	13	1.27021	1.15604	1.28404	0.36886
11	1	1	10	2500	493	53	15	1.23646	1.12708	0.81542	0.39770
12	1	1	10	2638	625	73	10	1.25980	1.15562	1.02440	0.32175
13	1	1	10	3118	815	77	47	1.33240	1.19366	1.07062	0.75538
14	1	1	10	1929	605	43	12	1.12385	1.15141	0.71517	0.35374
15	1	2	5	3031	575	77	2	1.32011	1.14503	1.07062	0.14190
16	1	2	5	2528	727	100	10	1.24130	1.17645	1.57080	0.32175
17	1	2	5	2653	592	77	3	1.26226	1.14866	1.07062	0.17408
18	1	2	5	2608	849	65	35	1.25483	1.20013	0.93774	0.63305
19	1	2	5	3258	513	95	8	1.35147	1.13152	1.34528	0.28676
20	1	2	5	2813	602	82	13	1.28769	1.15078	1.13265	0.36886
21	1	2	5	.	517	27	7	.	1.13241	0.54640	0.26776
22	1	2	10	3128	.	47	0	1.33379	.	0.75538	0.00000
23	1	2	10	2056	634	25	20	1.15154	1.15750	0.52360	0.46365
24	1	2	10	2854	523	38	0	1.29398	1.13373	0.66422	0.00000
25	1	2	10	2377	549	70	13	1.21455	1.13941	0.99116	0.36886
26	1	2	10	2867	617	63	3	1.29595	1.15394	0.91691	0.17408
27	1	2	10	.	356	32	0	.	1.09533	0.60126	0.00000
28	1	2	10	3238	679	70	8	1.34880	1.16677	0.99116	0.28676
29	2	1	5	3169	826	70	60	1.33944	1.19576	0.99116	0.88608
30	2	1	5	3169	891	100	67	1.33944	1.20799	1.57080	0.95886
31	2	1	5	2630	1105	98	75	1.25848	1.24598	1.42890	1.04720
32	2	1	5	3203	978	57	28	1.34408	1.22384	0.85563	0.55760
33	2	1	5	3259	1062	78	60	1.35161	1.23860	1.08259	0.88608
34	2	1	5	3349	1020	53	43	1.36344	1.23128	0.81542	0.71517
35	2	1	5	2539	1093	97	63	1.24318	1.24393	1.39671	0.91691
36	2	1	10	2595	914	75	32	1.25266	1.21224	1.04720	0.60126
37	2	1	10	3663	1237	95	47	1.40236	1.26785	1.34528	0.75538
38	2	1	10	2794	1277	62	48	1.28475	1.27427	0.90658	0.76539
39	2	1	10	2779	1149	88	77	1.28241	1.25339	1.21705	1.07062
40	2	1	10	2697	1252	80	65	1.26940	1.27027	1.10715	0.93774
41	2	1	10	2932	899	83	53	1.30569	1.20947	1.14581	0.81542
42	2	1	10	2208	757	30	18	1.18252	1.18240	0.57964	0.43815
43	2	2	5	3115	604	87	23	1.33198	1.15120	1.20193	0.50018
44	2	2	5	3027	940	87	68	1.31953	1.21699	1.20193	0.96953
45	2	2	5	2845	811	83	7	1.29260	1.19289	1.14581	0.26776
46	2	2	5	2818	685	93	12	1.28846	1.16799	1.30303	0.35374
47	2	2	5	3094	814	77	43	1.32904	1.19347	1.07062	0.71517
48	2	2	5	2779	884	98	68	1.28241	1.20669	1.42890	0.96953
49	2	2	5	2662	770	97	38	1.26373	1.18495	1.39671	0.66422

Table B2. Continued

50	2	2	10	2776	988	97	67	1.28194	1.22562	1.39671	0.95886
51	2	2	10	2836	807	95	25	1.29123	1.19212	1.34528	0.52360
52	2	2	10	2844	763	83	13	1.29245	1.18358	1.14581	0.36886
53	2	2	10	2889	1068	97	67	1.29927	1.23964	1.39671	0.95886
54	2	2	10	2781	1118	100	87	1.28272	1.24818	1.57080	1.20193
55	2	2	10	2917	1033	67	78	1.30346	1.23356	0.95886	1.08259
56	2	2	10	2394	672	77	27	1.21765	1.16534	1.07062	0.54640
57	3	1	5	3405	1444	95	95	1.37064	1.30008	1.34528	1.34528
58	3	1	5	2638	1152	100	100	1.25980	1.25389	1.57080	1.57080
59	3	1	5	2614	1262	90	93	1.25583	1.27187	1.24905	1.30303
60	3	1	5	2755	1204	87	83	1.27864	1.26248	1.20193	1.14581
61	3	1	5	2614	1179	92	80	1.25583	1.25837	1.28404	1.10715
62	3	1	5	2750	1237	95	92	1.27785	1.26785	1.34528	1.28404
63	3	1	5	3432	1237	75	57	1.37407	1.26785	1.04720	0.85563
64	3	1	10	3196	1263	55	28	1.34313	1.27203	0.83548	0.55760
65	3	1	10	3342	1263	77	88	1.36253	1.27203	1.07062	1.21705
66	3	1	10	3078	1425	90	93	1.32679	1.29722	1.24905	1.30303
67	3	1	10	3122	1323	83	58	1.33295	1.28153	1.14581	0.86574
68	3	1	10	2832	1222	92	85	1.29061	1.26542	1.28404	1.17310
69	3	1	10	2888	1420	75	87	1.29912	1.29646	1.04720	1.20193
70	3	1	10	2650	1427	98	100	1.26177	1.29752	1.42890	1.57080
71	3	2	5	2634	1330	98	93	1.25914	1.28262	1.42890	1.30303
72	3	2	5	2785	1257	75	73	1.28335	1.27107	1.04720	1.02440
73	3	2	5	2985	1299	92	82	1.31347	1.27775	1.28404	1.13265
74	3	2	5	3221	1448	78	90	1.34651	1.30068	1.08259	1.24905
75	3	2	5	2912	1014	60	73	1.30271	1.23023	0.88608	1.02440
76	3	2	5	2634	1247	98	90	1.25914	1.26946	1.42890	1.24905
77	3	2	5	2593	1215	98	98	1.25232	1.26428	1.42890	1.42890
78	3	2	10	3136	1436	73	58	1.33490	1.29887	1.02440	0.86574
79	3	2	10	3117	1484	77	97	1.33226	1.30604	1.07062	1.39671
80	3	2	10	2574	1325	67	80	1.24913	1.28184	0.95886	1.10715
81	3	2	10	2936	1462	92	97	1.30628	1.30277	1.28404	1.39671
82	3	2	10	2926	1487	90	100	1.30480	1.30648	1.24905	1.57080
83	3	2	10	2601	1138	97	95	1.25366	1.25155	1.39671	1.34528
84	3	2	10	2659	1302	93	80	1.26324	1.27823	1.30303	1.10715
85	4	1	5	2863	1442	87	95	1.29534	1.29978	1.20193	1.34528
86	4	1	5	3501	1390	93	95	1.38271	1.29190	1.30303	1.34528
87	4	1	5	2736	1295	92	88	1.27564	1.27712	1.28404	1.21705
88	4	1	5	2284	1114	93	98	1.19722	1.24750	1.30303	1.42890
89	4	1	5	3136	1311	92	83	1.33490	1.27965	1.28404	1.14581
90	4	1	5	2662	876	78	70	1.26373	1.20520	1.08259	0.99116
91	4	1	5	2756	1187	100	67	1.27880	1.25969	1.57080	0.95886
92	4	1	10	2939	1363	100	100	1.30672	1.28775	1.57080	1.57080
93	4	1	10	2700	1330	98	100	1.26989	1.28262	1.42890	1.57080
94	4	1	10	2762	1131	100	100	1.27975	1.25037	1.57080	1.57080
95	4	1	10	3152	1411	100	80	1.33711	1.29510	1.57080	1.10715
96	4	1	10	3168	1512	93	100	1.33931	1.31016	1.30303	1.57080
97	4	1	10	2790	1293	87	100	1.28413	1.27681	1.20193	1.57080
98	4	1	10	2965	1293	78	93	1.31055	1.27681	1.08259	1.30303
99	4	2	5	2816	1322	98	93	1.28815	1.28137	1.42890	1.30303

Table B2. Continued

100	4	2	5	3028	1038	95	87	1.31968	1.23444	1.34528	1.20193
101	4	2	5	3379	1438	82	72	1.36731	1.29917	1.13265	1.01320
102	4	2	5	3011	1308	95	98	1.31723	1.27917	1.34528	1.42890
103	4	2	5	3059	1363	44	90	1.32410	1.28775	0.72525	1.24905
104	4	2	5	3256	1164	73	.	1.35121	1.25589	1.02440	.
105	4	2	5	2584	1251	92	97	1.25081	1.27011	1.28404	1.39671
106	4	2	10	2805	1258	87	98	1.28645	1.27123	1.20193	1.42890
107	4	2	10	2866	1383	100	98	1.29580	1.29082	1.57080	1.42890
108	4	2	10	2930	1431	88	100	1.30539	1.29812	1.21705	1.57080
109	4	2	10	2536	1507	88	100	1.24267	1.30943	1.21705	1.57080
110	4	2	10	3003	1480	95	83	1.31608	1.30544	1.34528	1.14581
111	4	2	10	2736	1174	70	100	1.27564	1.25755	0.99116	1.57080
112	4	2	10	2919	1406	95	100	1.30376	1.29434	1.34528	1.57080
113	5	1	5	3279	943	78	25	1.35426	1.21753	1.08259	0.52360
114	5	1	5	3178	595	67	10	1.34068	1.14929	0.95886	0.32175
115	5	1	5	3605	717	93	43	1.39543	1.17445	1.30303	0.71517
116	5	1	5	2936	695	65	10	1.30628	1.17002	0.93774	0.32175
117	5	1	5	2726	644	78	12	1.27405	1.15957	1.08259	0.35374
118	5	1	5	2881	748	60	15	1.29806	1.18062	0.88608	0.39770
119	5	1	5	2755	422	80	13	1.27864	1.11091	1.10715	0.36886
120	5	1	10	2694	821	93	12	1.26892	1.19481	1.30303	0.35374
121	5	1	10	2889	1460	92	77	1.29927	1.30247	1.28404	1.07062
122	5	1	10	3028	1423	95	88	1.31968	1.29691	1.34528	1.21705
123	5	1	10	2819	659	83	17	1.28862	1.16267	1.14581	0.42499
124	5	1	10	2693	1008	100	32	1.26876	1.22917	1.57080	0.60126
125	5	1	10	3174	624	65	12	1.34013	1.15541	0.93774	0.35374
126	5	1	10	3110	1487	67	.	1.33128	1.30648	0.95886	.
127	5	2	5	2971	660	80	13	1.31142	1.16288	1.10715	0.36886
128	5	2	5	2717	800	100	20	1.27261	1.19078	1.57080	0.46365
129	5	2	5	2630	997	100	10	1.25848	1.22722	1.57080	0.32175
130	5	2	5	3318	.	58	0	1.35940	.	0.86574	0.00000
131	5	2	5	2907	617	40	10	1.30197	1.15394	0.68472	0.32175
132	5	2	5	3031	962	73	33	1.32011	1.22097	1.02440	0.61194
133	5	2	5	2689	528	98	3	1.26811	1.13483	1.42890	0.17408
134	5	2	10	2348	1330	95	93	1.20922	1.28262	1.34528	1.30303
135	5	2	10	2734	762	78	25	1.27532	1.18338	1.08259	0.52360
136	5	2	10	2624	1123	90	70	1.25749	1.24902	1.24905	0.99116
137	5	2	10	2741	1025	77	38	1.27643	1.23216	1.07062	0.66422
138	5	2	10	3151	661	75	58	1.33697	1.16309	1.04720	0.86574
139	5	2	10	2397	1191	93	92	1.21819	1.26035	1.30303	1.28404
140	5	2	10	2483	1211	98	87	1.23350	1.26363	1.42890	1.20193

Table B3. Means of Treatment Groups: Shear Strength Dry and Wet (LOG10 of MPa) and Wood Failure Dry and Wet (ARCSINSQRT of Percentage Fraction)

T=1 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2639338	0.0017741	0.0421199	3.3324432
LOGSH_W	7	1.1378042	0.000833449	0.0288695	2.5373009
ARWF_D	7	1.0227114	0.0621545	0.2493080	24.3771580
ARWF_W	7	0.2187215	0.0648210	0.2545996	116.4035806

T=1 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2559231	0.0042924	0.0655166	5.2166113
LOGSH_W	7	1.1579115	0.000420525	0.0205067	1.7710085
ARWF_D	7	0.9644678	0.0781701	0.2795892	28.9889659
ARWF_W	7	0.5238197	0.0442071	0.2102549	40.1387868

T=1 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	6	1.2862764	0.0017972	0.0423931	3.2957990
LOGSH_W	7	1.1549962	0.000619356	0.0248869	2.1547148
ARWF_D	7	1.0963007	0.1028848	0.3207566	29.2580879
ARWF_W	7	0.3134522	0.0261564	0.1617293	51.5961650

T=1 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	6	1.2731013	0.0057150	0.0755975	5.9380585
LOGSH_W	6	1.1411134	0.000649000	0.0254755	2.2325103
ARWF_D	7	0.7776687	0.0365968	0.1913028	24.5995279
ARWF_W	7	0.1847643	0.0374330	0.1934762	104.7151461

T=2 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3199530	0.0023179	0.0481443	3.6474280
LOGSH_W	7	1.2267695	0.000357729	0.0189137	1.5417510
ARWF_D	7	1.1630288	0.0904849	0.3008071	25.8641138
ARWF_W	7	0.8525549	0.0269082	0.1640372	19.2406597

Table B3. Continued

T=2 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2828264	0.0043276	0.0657848	5.1281148
LOGSH_W	7	1.2385537	0.0013419	0.0366316	2.9576087
ARWF_D	7	1.0498160	0.0615600	0.2481128	23.6339295
ARWF_W	7	0.7691377	0.0432330	0.2079254	27.0335751

T=2 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3011089	0.000675310	0.0259867	1.9972748
LOGSH_W	7	1.1877401	0.000501122	0.0223858	1.8847354
ARWF_D	7	1.2498481	0.0173329	0.1316544	10.5336340
ARWF_W	7	0.6343045	0.0772077	0.2778627	43.8058829

T=2 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2812452	0.000848509	0.0291292	2.2735060
LOGSH_W	7	1.2125780	0.0010168	0.0318879	2.6297604
ARWF_D	7	1.2692553	0.0467070	0.2161181	17.0271602
ARWF_W	7	0.8058714	0.1030378	0.3209951	39.8320479

T=3 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2960938	0.0028058	0.0529694	4.0868517
LOGSH_W	7	1.2689129	0.000226704	0.0150567	1.1865819
ARWF_D	7	1.2919398	0.0255590	0.1598719	12.3745639
ARWF_W	7	1.2302482	0.0500034	0.2236144	18.1763690

T=3 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3167004	0.0011953	0.0345731	2.6257398
LOGSH_W	7	1.2831714	0.000190953	0.0138186	1.0769082
ARWF_D	7	1.1515841	0.0368922	0.1920734	16.6790638
ARWF_W	7	1.1270367	0.1060442	0.3256443	28.8938509

Table B3. Continued

T=3 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2880911	0.0012082	0.0347590	2.6984921
LOGSH_W	7	1.2708702	0.000461867	0.0214911	1.6910531
ARWF_D	7	1.2266576	0.0491590	0.2217183	18.0749918
ARWF_W	7	1.2016375	0.0223355	0.1494506	12.4372482

T=3 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2920375	0.0013272	0.0364310	2.8196533
LOGSH_W	7	1.2893966	0.000408611	0.0202141	1.5677194
ARWF_D	7	1.1838144	0.0271122	0.1646579	13.9090956
ARWF_W	7	1.2556495	0.0572136	0.2391936	19.0493880

T=4 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2897630	0.0033784	0.0581237	4.5065393
LOGSH_W	7	1.2658335	0.0010333	0.0321447	2.5394104
ARWF_D	7	1.2899238	0.0216719	0.1472139	11.4126009
ARWF_W	7	1.2046201	0.0332422	0.1823244	15.1354270

T=4 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3039199	0.000756665	0.0275076	2.1096046
LOGSH_W	7	1.2828017	0.000341294	0.0184741	1.4401397
ARWF_D	7	1.3898351	0.0395012	0.1987492	14.3002005
ARWF_W	7	1.4663091	0.0350405	0.1871912	12.7661460

T=4 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3169279	0.0014952	0.0386682	2.9362440
LOGSH_W	7	1.2725571	0.000466298	0.0215939	1.6968927
ARWF_D	7	1.1836859	0.0600944	0.2451416	20.7100236
ARWF_W	6	1.2654704	0.0226586	0.1505277	11.8950025

Table B3. Continued

T=4 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2893976	0.000599337	0.0244814	1.8986666
LOGSH_W	7	1.2895611	0.000350928	0.0187331	1.4526698
ARWF_D	7	1.2697945	0.0316344	0.1778606	14.0070358
ARWF_W	7	1.4695416	0.0248529	0.1576480	10.7277011

T=5 S=1 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3210570	0.0019624	0.0442988	3.3532839
LOGSH_W	7	1.1660589	0.0010520	0.0324343	2.7815306
ARWF_D	7	1.0511489	0.0195310	0.1397533	13.2952913
ARWF_W	7	0.4289388	0.0206843	0.1438203	33.5293238

T=5 S=1 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.3023788	0.000834775	0.0288925	2.2184392
LOGSH_W	7	1.2354175	0.0044515	0.0667194	5.4005525
ARWF_D	7	1.2207944	0.0505189	0.2247642	18.4113043
ARWF_W	6	0.6702346	0.1449112	0.3806721	56.7968394

T=5 S=2 C=5

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2988711	0.0012582	0.0354706	2.7308801
LOGSH_W	6	1.1817683	0.0014036	0.0374647	3.1702202
ARWF_D	7	1.1789284	0.1234944	0.3514177	29.8082330
ARWF_W	7	0.3231478	0.0386466	0.1965874	60.8351298

T=5 S=2 C=10

Variable	N	Mean	Variance	Std Dev	CV
LOGSH_D	7	1.2581592	0.0019068	0.0436668	3.4706900
LOGSH_W	7	1.2334645	0.0019591	0.0442621	3.5884351
ARWF_D	7	1.2180952	0.0230175	0.1517150	12.4551055
ARWF_W	7	0.9762457	0.0945246	0.3074485	31.4929382

Table B4. ANOVA on the Variable Shear Strength Dry (LOG10 of MPa)

General Linear Models Procedure

Dependent Variable: LOGSH_D

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.0493458	0.0025971	1.30	0.1950
Error	118	0.2353449	0.0019944		
Corrected Total	137	0.2846908			

R-Square	C.V.	Root MSE	LOGSH_D Mean
0.173331	3.456424	0.0447	1.2921

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	0.0173609	0.0043402	2.18	0.0758
S	1	0.0017604	0.0017604	0.88	0.3494
C	1	0.0055041	0.0055041	2.76	0.0993
T*S	4	0.0113567	0.0028392	1.42	0.2304
T*C	4	0.0084225	0.0021056	1.06	0.3817
S*C	1	0.0016382	0.0016382	0.82	0.3666
T*S*C	4	0.0033030	0.0008257	0.41	0.7983

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	0.0163862	0.0040965	2.05	0.0912
S	1	0.0015608	0.0015608	0.78	0.3782
C	1	0.0054991	0.0054991	2.76	0.0995
T*S	4	0.0113567	0.0028392	1.42	0.2304
T*C	4	0.0084168	0.0021042	1.06	0.3820
S*C	1	0.0016051	0.0016051	0.80	0.3715
T*S*C	4	0.0033030	0.0008257	0.41	0.7983

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
5 VS OTH	1	0.0003632	0.0003632	0.18	0.6703
1 VS 2-4	1	0.0159003	0.0159003	7.97	0.0056
2 VS 3+4	1	0.0001498	0.0001498	0.08	0.7845
3 VS 4	1	0.0000439	0.0000439	0.02	0.8823

Table B5. DMRT on the HMR Drying Time of the Variable Shear Strength Dry (LOG10 of MPa)

```
               General Linear Models Procedure

     Duncan's Multiple Range Test for variable: LOGSH_D

NOTE: This test controls the type I comparisonwise error rate,
      not the experimentwise error rate

            Alpha= 0.05  df= 118  MSE= 0.001994
             WARNING: Cell sizes are not equal.
           Harmonic Mean of cell sizes= 27.57576

        Number of Means      2      3      4      5
        Critical Range  .02389 .02512 .02592 .02651

Means with the same letter are not significantly different.

        Duncan Grouping              Mean       N  T

                      A           1.30000      28  4
                      A
                      A           1.29823      28  3
                      A
                      A           1.29628      28  2
                      A
                      A           1.29512      28  5

                      B           1.26905      26  1
```

Table B6. DMRT on the HMR Spread Rate of the Variable Shear Strength Dry (LOG10 of MPa)

```
               General Linear Models Procedure

     Duncan's Multiple Range Test for variable: LOGSH_D

NOTE: This test controls the type I comparisonwise error rate,
      not the experimentwise error rate

            Alpha= 0.05  df= 118  MSE= 0.001994
             WARNING: Cell sizes are not equal.
           Harmonic Mean of cell sizes= 68.98551

                  Number of Means      2
                  Critical Range  .01511

Means with the same letter are not significantly different.

        Duncan Grouping              Mean       N  S

                      A          1.295255      70  1
                      A
                      A          1.288781      68  2
```

Table B7. DMRT on the HMR Solids Content of the Variable Shear Strength Dry (LOG10 of MPa)

```
               General Linear Models Procedure

      Duncan's Multiple Range Test for variable: LOGSH_D

NOTE: This test controls the type I comparisonwise error rate,
      not the experimentwise error rate

             Alpha= 0.05  df= 118  MSE= 0.001994

                    Number of Means      2
                    Critical Range  .01510

Means with the same letter are not significantly different.

        Duncan Grouping              Mean      N  C

                      A          1.298381     69  5
                      A
                      A          1.285750     69  10
```

Table B8. ANOVA on the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

General Linear Models Procedure

Dependent Variable: ARWF_D

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	2.5440853	0.1338992	2.67	0.0007
Error	120	6.0244631	0.0502039		
Corrected Total	139	8.5685484			

R-Square	C.V.	Root MSE	ARWF_D Mean
0.296910	19.27475	0.2241	1.1625

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	1.5828683	0.3957171	7.88	0.0001
S	1	0.0012101	0.0012101	0.02	0.8769
C	1	0.0234870	0.0234870	0.47	0.4953
T*S	4	0.3042528	0.0760632	1.52	0.2021
T*C	4	0.4360675	0.1090169	2.17	0.0763
S*C	1	0.0106622	0.0106622	0.21	0.6457
T*S*C	4	0.1855375	0.0463844	0.92	0.4525

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	1.5828683	0.3957171	7.88	0.0001
S	1	0.0012101	0.0012101	0.02	0.8769
C	1	0.0234870	0.0234870	0.47	0.4953
T*S	4	0.3042528	0.0760632	1.52	0.2021
T*C	4	0.4360675	0.1090169	2.17	0.0763
S*C	1	0.0106622	0.0106622	0.21	0.6457
T*S*C	4	0.1855375	0.0463844	0.92	0.4525

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
5 VS OTH	1	0.0007986	0.0007986	0.02	0.8998
1 VS 2-4	1	1.4339573	1.4339573	28.56	0.0001
2 VS 3+4	1	0.0798827	0.0798827	1.59	0.2096
3 VS 4	1	0.0682297	0.0682297	1.36	0.2460

Table B9. DMRT on the HMR Drying Time of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

```
              General Linear Models Procedure

      Duncan's Multiple Range Test for variable: ARWF_D

NOTE: This test controls the type I comparisonwise error rate,
      not the experimentwise error rate

           Alpha= 0.05  df= 120  MSE= 0.050204

         Number of Means     2     3     4     5
         Critical Range  .1190 .1251 .1290 .1320

Means with the same letter are not significantly different.

        Duncan Grouping              Mean      N  T

                     A            1.28331     28  4
                     A
                     A            1.21350     28  3
                     A
                     A            1.18299     28  2
                     A
                     A            1.16724     28  5

                     B            0.96529     28  1
```

Table B10. DMRT on the HMR Spread Rate of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

```
              General Linear Models Procedure

      Duncan's Multiple Range Test for variable: ARWF_D

NOTE: This test controls the type I comparisonwise error rate,
      not the experimentwise error rate

           Alpha= 0.05  df= 120  MSE= 0.050204

                  Number of Means      2
                  Critical Range  .07524

Means with the same letter are not significantly different.

        Duncan Grouping              Mean      N  S

                     A            1.16540     70  2
                     A
                     A            1.15952     70  1
```

Table B11. DMRT on the HMR Solids Content of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

```
                  General Linear Models Procedure

         Duncan's Multiple Range Test for variable: ARWF_D

    NOTE: This test controls the type I comparisonwise error rate,
          not the experimentwise error rate

                Alpha= 0.05  df= 120  MSE= 0.050204

                       Number of Means      2
                       Critical Range  .07524

    Means with the same letter are not significantly different.

            Duncan Grouping               Mean       N  C

                         A             1.17542      70  5
                         A
                         A             1.14951      70  10
```

Table B12. Normality Test on the Residuals of the Variable Shear Strength Dry (LOG10 of MPa)

Univariate Procedure

Variable=RES1

Moments

N	138	Sum Wgts	138
Mean	0	Sum	0
Std Dev	0.041447	Variance	0.001718
Skewness	-0.18016	Kurtosis	0.770393
USS	0.235345	CSS	0.235345
CV	.	Std Mean	0.003528
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	138	Num > 0	75
M(Sign)	6	Pr>=|M|	0.3491
Sgn Rank	25.5	Pr>=|S|	0.9570
W:Normal	0.985693	Pr<W	0.7754

Quantiles(Def=5)

100% Max	0.119532	99%	0.092951
75% Q3	0.022859	95%	0.074545
50% Med	0.002336	90%	0.050382
25% Q1	-0.0288	10%	-0.04673
0% Min	-0.13207	5%	-0.06611
		1%	-0.12156
Range	0.251601		
Q3-Q1	0.051657		
Mode	-0.04027		

Extremes

Lowest	Obs	Highest	Obs
-0.13207(	14)	0.076475(	13)
-0.12156(	23)	0.077975(	63)
-0.10031(	42)	0.078811(	138)
-0.09255(	88)	0.092951(	86)
-0.07677(	35)	0.119532(	37)

Missing Value	.
Count	2
% Count/Nobs	1.43

Table B13. Boxplot of the Residuals of the Variable Shear Strength Dry (LOG10 of MPa)

```
                         Univariate Procedure

Variable=RES1

             Stem Leaf                     #             Boxplot
               12 0                        1                0
               11
               10
                9 3                        1                |
                8                                           |
                7 456689                   6                |
                6 1158                     4                |
                5 08                       2                |
                4 003356                   6                |
                3 12334458                 8                |
                2 0011233456789           13             +-----+
                1 00133444456677788899    20             |     |
                0 01111233346677          14             *--+--*
               -0 9553310                  7             |     |
               -1 998875444331            12             |     |
               -2 999966654430            12             +-----+
               -3 87664431100             11                |
               -4 9775320000              10                |
               -5 95                       2                |
               -6 7641                     4                |
               -7 7                        1                |
               -8                                           |
               -9 3                        1                |
              -10 0                        1                |
              -11
              -12 2                        1                0
              -13 2                        1                0
                  ----+----+----+----+
              Multiply Stem.Leaf by 10**-2
```

Table B14. Normality Test on the Residuals of the Variable Shear Strength Wet (LOG10 of MPa)

Univariate Procedure

Variable=RES2

Moments

N	138	Sum Wgts	138
Mean	0	Sum	0
Std Dev	0.027877	Variance	0.000777
Skewness	-0.27243	Kurtosis	0.404696
USS	0.106463	CSS	0.106463
CV	.	Std Mean	0.002373
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	138	Num > 0	69
M(Sign)	0	Pr>=|M|	1.0000
Sgn Rank	173.5	Pr>=|S|	0.7138
W:Normal	0.980367	Pr<W	0.4547

Quantiles(Def=5)

100% Max	0.071063	99%	0.067052
75% Q3	0.015883	95%	0.045453
50% Med	0.000011	90%	0.031712
25% Q1	-0.01677	10%	-0.03785
0% Min	-0.08001	5%	-0.05009
		1%	-0.07274
Range	0.151073		
Q3-Q1	0.032648		
Mode	-0.01114		

Extremes

Lowest	Obs	Highest	Obs
-0.08001(	125)	0.051472(	113)
-0.07274(	123)	0.051812(	5)
-0.07038(	138)	0.061496(	122)
-0.06063(	90)	0.067052(	121)
-0.05616(	42)	0.071063(	126)

Missing Value	.
Count	2
% Count/Nobs	1.43

Table B15. Boxplot of the Residuals of the Variable Shear Strength Wet (LOG10 of MPa)

```
                    Univariate Procedure

Variable=RES2

         Stem Leaf                           #             Boxplot
            7 1                              1                0
            6 17                             2                0
            5 12                             2                |
            4 559                            3                |
            3 001246669                      9                |
            2 01166777799                   11                |
            1 1122233334444555666677799     25             +-----+
            0 0134555567789999              16             *--+--*
           -0 88777666666664332222211110    26             |     |
           -1 99888776511110                14             +-----+
           -2 998653300                      9                |
           -3 88722211                       8                |
           -4 77611                          5                |
           -5 650                            3                |
           -6 1                              1                |
           -7 30                             2                0
           -8 0                              1                0
              ----+----+----+----+----+-
          Multiply Stem.Leaf by 10**-2
```

Table B16. Normality Test on the Residuals of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

Univariate Procedure

Variable=RES3

Moments

N	140	Sum Wgts	140
Mean	0	Sum	0
Std Dev	0.208186	Variance	0.043341
Skewness	-0.18438	Kurtosis	-0.32605
USS	6.024463	CSS	6.024463
CV	.	Std Mean	0.017595
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	140	Num > 0	70
M(Sign)	0	Pr>=|M|	1.0000
Sgn Rank	102	Pr>=|S|	0.8329
W:Normal	0.979948	Pr<W	0.4256

Quantiles(Def=5)

100% Max	0.474496	99%	0.407768
75% Q3	0.154231	95%	0.319572
50% Med	0.005245	90%	0.271593
25% Q1	-0.14827	10%	-0.28084
0% Min	-0.5499	5%	-0.3441
		1%	-0.49421
Range	1.024396		
Q3-Q1	0.302496		
Mode	0.180961		

Extremes

Lowest	Obs	Highest	Obs
-0.5499(	21)	0.374002(	2)
-0.49421(	131)	0.391868(	128)
-0.47018(	42)	0.391868(	129)
-0.45843(	103)	0.407768(	30)
-0.40687(	9)	0.474496(	16)

Table B17. Boxplot of the Residuals of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

```
                     Univariate Procedure

Variable=RES3

            Stem Leaf                     #             Boxplot
               4 7                        1                |
               4 1                        1                |
               3 5799                     4                |
               3 00022                    5                |
               2 55557888                 8                |
               2 000111133                9                |
               1 56678888                 8             +-----+
               1 000012233334            12             |     |
               0 555666667888888         15             |     |
               0 1133344                  7             *--+--*
              -0 433211110                9             |     |
              -0 999988777555555         15             |     |
              -1 4442111100              10             |     |
              -1 98887776666555          14             +-----+
              -2 4210                     4                |
              -2 88655                    5                |
              -3 421111                   6                |
              -3 75                       2                |
              -4 1                        1                |
              -4 976                      3                |
              -5                                           |
              -5 5                        1                |
                 ----+----+----+----+
             Multiply Stem.Leaf by 10**-1
```

Table B18. Normality Test on the Residuals of the Variable Wood Failure Wet (ARCSINSQRT of Percentage Fraction)

Univariate Procedure

Variable=RES4

Moments

N	138	Sum Wgts	138
Mean	0	Sum	0
Std Dev	0.213955	Variance	0.045777
Skewness	-0.05075	Kurtosis	-0.33718
USS	6.271401	CSS	6.271401
CV	.	Std Mean	0.018213
T:Mean=0	0	Pr>|T|	1.0000
Num ¬= 0	138	Num > 0	72
M(Sign)	3	Pr>=|M|	0.6705
Sgn Rank	12.5	Pr>=|S|	0.9789
W:Normal	0.983551	Pr<W	0.6512

Quantiles(Def=5)

100% Max	0.54682	99%	0.445494
75% Q3	0.1405	95%	0.335228
50% Med	0.022411	90%	0.291596
25% Q1	-0.16328	10%	-0.29496
0% Min	-0.56944	5%	-0.35916
		1%	-0.45265
Range	1.116258		
Q3-Q1	0.303776		
Mode	0.104487		

Extremes

Lowest	Obs	Highest	Obs
-0.56944(	64)	0.396062(	54)
-0.45265(	135)	0.400382(	121)
-0.43701(	52)	0.44376(	70)
-0.38991(	78)	0.445494(	5)
-0.37462(	63)	0.54682(	122)

Missing Value	.
Count	2
% Count/Nobs	1.43

Table B19. Boxplot of the Residuals of the Variable Wood Failure Wet (ARCSINSQRT of Percentage Fraction)

```
                         Univariate Procedure

Variable=RES4

               Stem Leaf                     #             Boxplot
                  5 5                        1                |
                  5                                           |
                  4 5                        1                |
                  4 004                      3                |
                  3                                           |
                  3 01223444                 8                |
                  2 88999                    5                |
                  2 12333                    5                |
                  1 5567889                  7                |
                  1 00000000000123344444    20             +-----+
                  0 555555566778999         15             |     |
                  0 1113334                  7             *--+--*
                 -0 44433211000             11             |     |
                 -0 88776665                 8             |     |
                 -1 44332111                 8             |     |
                 -1 8888877765555           13             +-----+
                 -2 22210                    5                |
                 -2 98866555                 8                |
                 -3 322221                   6                |
                 -3 9776                     4                |
                 -4 4                        1                |
                 -4 5                        1                |
                 -5                                           |
                 -5 7                        1                |
                    ----+----+----+----+
                Multiply Stem.Leaf by 10**-1
```

Table B20. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Shear Strength Dry (LOG10 of MPa)

General Linear Models Procedure

Dependent Variable: RES1AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.0132885	0.0006994	1.04	0.4187
Error	118	0.0791161	0.0006705		
Corrected Total	137	0.0924046			

R-Square	C.V.	Root MSE	RES1AB Mean
0.143808	80.45509	0.0259	0.0322

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	0.0030274	0.0007569	1.13	0.3463
S	1	0.0009385	0.0009385	1.40	0.2391
C	1	0.0000586	0.0000586	0.09	0.7680
T*S	4	0.0034660	0.0008665	1.29	0.2770
T*C	4	0.0041875	0.0010469	1.56	0.1891
S*C	1	0.0009505	0.0009505	1.42	0.2362
T*S*C	4	0.0006600	0.0001650	0.25	0.9115

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	0.0032044	0.0008011	1.19	0.3168
S	1	0.0008531	0.0008531	1.27	0.2616
C	1	0.0000282	0.0000282	0.04	0.8378
T*S	4	0.0034660	0.0008665	1.29	0.2770
T*C	4	0.0043040	0.0010760	1.60	0.1776
S*C	1	0.0009555	0.0009555	1.43	0.2350
T*S*C	4	0.0006600	0.0001650	0.25	0.9115

Table B21. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Shear Strength Wet (LOG10 of MPa)

General Linear Models Procedure

Dependent Variable: RES2AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.0159458	0.0008393	3.68	0.0001
Error	118	0.0269148	0.0002281		
Corrected Total	137	0.0428606			

R-Square	C.V.	Root MSE	RES2AB Mean
0.372038	70.34869	0.0151	0.0215

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	0.0090496	0.0022624	9.92	0.0001
S	1	0.0000533	0.0000533	0.23	0.6296
C	1	0.0007760	0.0007760	3.40	0.0676
T*S	4	0.0004604	0.0001151	0.50	0.7324
T*C	4	0.0036602	0.0009151	4.01	0.0044
S*C	1	0.0001255	0.0001255	0.55	0.4598
T*S*C	4	0.0018208	0.0004552	2.00	0.0996

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	0.0088686	0.0022172	9.72	0.0001
S	1	0.0000586	0.0000586	0.26	0.6133
C	1	0.0007758	0.0007758	3.40	0.0677
T*S	4	0.0004514	0.0001129	0.49	0.7396
T*C	4	0.0035149	0.0008787	3.85	0.0056
S*C	1	0.0001338	0.0001338	0.59	0.4452
T*S*C	4	0.0018208	0.0004552	2.00	0.0996

Table B22. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Wood Failure Dry (ARCSINSQRT of Percentage Fraction)

General Linear Models Procedure

Dependent Variable: RES3AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.3796189	0.0199799	1.50	0.0989
Error	120	1.6032364	0.0133603		
Corrected Total	139	1.9828554			

R-Square	C.V.	Root MSE	RES3AB Mean
0.191451	68.02916	0.1156	0.1699

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	0.0666907	0.0166727	1.25	0.2944
S	1	0.0029575	0.0029575	0.22	0.6389
C	1	0.0052451	0.0052451	0.39	0.5321
T*S	4	0.0915618	0.0228905	1.71	0.1515
T*C	4	0.0121096	0.0030274	0.23	0.9231
S*C	1	0.0542754	0.0542754	4.06	0.0461
T*S*C	4	0.1467788	0.0366947	2.75	0.0315

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	0.0666907	0.0166727	1.25	0.2944
S	1	0.0029575	0.0029575	0.22	0.6389
C	1	0.0052451	0.0052451	0.39	0.5321
T*S	4	0.0915618	0.0228905	1.71	0.1515
T*C	4	0.0121096	0.0030274	0.23	0.9231
S*C	1	0.0542754	0.0542754	4.06	0.0461
T*S*C	4	0.1467788	0.0366947	2.75	0.0315

Table B23. Levine's Test for Equality of Variances on the Absolute Residuals of the Variable Wood Failure Wet (ARCSINSQRT of Percentage Fraction)

General Linear Models Procedure

Dependent Variable: RES4AB

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.4633984	0.0243894	1.75	0.0365
Error	118	1.6408499	0.0139055		
Corrected Total	137	2.1042482			

R-Square	C.V.	Root MSE	RES4AB Mean
0.220220	67.85991	0.1179	0.1738

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	0.0786679	0.0196670	1.41	0.2334
S	1	0.0012968	0.0012968	0.09	0.7606
C	1	0.1169417	0.1169417	8.41	0.0045
T*S	4	0.1396419	0.0349105	2.51	0.0454
T*C	4	0.1030500	0.0257625	1.85	0.1234
S*C	1	0.0001013	0.0001013	0.01	0.9321
T*S*C	4	0.0236989	0.0059247	0.43	0.7896

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	4	0.0860433	0.0215108	1.55	0.1931
S	1	0.0022128	0.0022128	0.16	0.6907
C	1	0.1208611	0.1208611	8.69	0.0039
T*S	4	0.1395246	0.0348811	2.51	0.0456
T*C	4	0.1053663	0.0263416	1.89	0.1159
S*C	1	0.0000611	0.0000611	0.00	0.9473
T*S*C	4	0.0236989	0.0059247	0.43	0.7896

Table B24. Summary of Laminate Strength Properties

Laminate	Drying Time	Spread Rate	Solids Content	Dry Conditions		Wet Conditions	
				Shear Strength	Wood Failure	Shear Strength	Wood Failure
	min/h	g/m^2	%	MPa	%	MPa	%
1	5	146	5	19.230	80	3.551	7
2	5	146	5	15.734	97	2.958	0
3	5	146	5	21.464	58	3.247	3
4	5	146	5	18.974	68	4.233	17
5	5	146	5	17.127	90	5.474	38
6	5	146	5	18.395	63	2.758	0
7	5	146	5	18.133	37	4.102	0
8	5	146	10	18.761	92	4.840	37
9	5	146	10	19.747	28	4.130	53
10	5	146	10	18.630	92	4.323	13
11	5	146	10	17.237	53	3.399	15
12	5	146	10	18.188	73	4.309	10
13	5	146	10	21.498	77	5.619	47
14	5	146	10	13.300	43	4.171	12
15	5	220	5	20.898	77	3.965	2
16	5	220	5	17.430	100	5.013	10
17	5	220	5	18.292	77	4.082	3
18	5	220	5	17.982	65	5.854	35
19	5	220	5	22.463	95	3.537	8
20	5	220	5	19.395	82	4.151	13
21	5	220	5	9.694	27	3.565	7
22	5	220	10	21.567	47	1.648	0
23	5	220	10	14.176	25	4.371	20
24	5	220	10	19.678	38	3.606	0
25	5	220	10	16.389	70	3.785	13
26	5	220	10	19.767	63	4.254	3
27	5	220	10	9.618	32	2.455	0
28	5	220	10	22.325	70	4.682	8
29	10	146	5	21.850	70	5.695	60
30	10	146	5	21.850	100	6.143	67
31	10	146	5	18.133	98	7.619	75
32	10	146	5	22.084	57	6.743	28
33	10	146	5	22.470	78	7.322	60
34	10	146	5	23.091	53	7.033	43
35	10	146	5	17.506	97	7.536	63
36	10	146	10	17.892	75	6.302	32
37	10	146	10	25.256	95	8.529	47
38	10	146	10	19.264	62	8.805	48
39	10	146	10	19.161	88	7.922	77
40	10	146	10	18.595	80	8.632	65

Table B24. Continued

41	10	146	10	20.216	83	6.198	53
42	10	146	10	15.224	30	5.219	18
43	10	220	5	21.477	87	4.164	23
44	10	220	5	20.871	87	6.481	68
45	10	220	5	19.616	83	5.592	7
46	10	220	5	19.430	93	4.723	12
47	10	220	5	21.333	77	5.612	43
48	10	220	5	19.161	98	6.095	68
49	10	220	5	18.354	97	5.309	38
50	10	220	10	19.140	97	6.812	67
51	10	220	10	19.554	95	5.564	25
52	10	220	10	19.609	83	5.261	13
53	10	220	10	19.919	97	7.364	67
54	10	220	10	19.174	100	7.708	87
55	10	220	10	20.112	67	7.122	78
56	10	220	10	16.506	77	4.633	27
57	15	146	5	23.477	95	9.956	95
58	15	146	5	18.188	100	7.943	100
59	15	146	5	18.023	90	8.701	93
60	15	146	5	18.995	87	8.301	83
61	15	146	5	18.023	92	8.129	80
62	15	146	5	18.961	95	8.529	92
63	15	146	5	23.663	75	8.529	57
64	15	146	10	22.036	55	8.708	28
65	15	146	10	23.042	77	8.708	88
66	15	146	10	21.222	90	9.825	93
67	15	146	10	21.526	83	9.122	58
68	15	146	10	19.526	92	8.425	85
69	15	146	10	19.912	75	9.791	87
70	15	146	10	18.271	98	9.839	100
71	15	220	5	18.161	98	9.170	93
72	15	220	5	19.202	75	8.667	73
73	15	220	5	20.581	92	8.956	82
74	15	220	5	22.208	78	9.984	90
75	15	220	5	20.078	60	6.991	73
76	15	220	5	18.161	98	8.598	90
77	15	220	5	17.878	98	8.377	98
78	15	220	10	21.622	73	9.901	58
79	15	220	10	21.491	77	10.232	97
80	15	220	10	17.747	67	9.136	80

Table B24. Continued

81	15	220	10	20.243	92	10.080	97
82	15	220	10	20.174	90	10.253	100
83	15	220	10	17.933	97	7.846	95
84	15	220	10	18.333	93	8.977	80
85	20	146	5	19.740	87	9.942	95
86	20	146	5	24.139	93	9.584	95
87	20	146	5	18.864	92	8.929	88
88	20	146	5	15.748	93	7.681	98
89	20	146	5	21.622	92	9.039	83
90	20	146	5	18.354	78	6.040	70
91	20	146	5	19.002	100	8.184	67
92	20	146	10	20.264	100	9.398	100
93	20	146	10	18.616	98	9.170	100
94	20	146	10	19.043	100	7.798	100
95	20	146	10	21.732	100	9.729	80
96	20	146	10	21.843	93	10.425	100
97	20	146	10	19.236	87	8.915	100
98	20	146	10	20.443	78	8.915	93
99	20	220	5	19.416	98	9.115	93
100	20	220	5	20.877	95	7.157	87
101	20	220	5	23.298	82	9.915	72
102	20	220	5	20.760	95	9.018	98
103	20	220	5	21.091	44	9.398	90
104	20	220	5	22.449	73	8.026	17
105	20	220	5	17.816	92	8.625	97
106	20	220	10	19.340	87	8.674	98
107	20	220	10	19.760	100	9.536	98
108	20	220	10	20.202	88	9.866	100
109	20	220	10	17.485	88	10.390	100
110	20	220	10	20.705	95	10.204	83
111	20	220	10	18.864	70	8.094	100
112	20	220	10	20.126	95	9.694	100
113	standard	146	5	22.608	78	6.502	25
114	standard	146	5	21.912	67	4.102	10
115	standard	146	5	24.856	93	4.944	43
116	standard	146	5	20.243	65	4.792	10
117	standard	146	5	18.795	78	4.440	12
118	standard	146	5	19.864	60	5.157	15
119	standard	146	5	18.995	80	2.910	13
120	standard	146	10	18.575	93	5.661	12

Table B24. Continued

121	standard	146	10	19.919	92	10.066	77
122	standard	146	10	20.877	95	9.811	88
123	standard	146	10	19.436	83	4.544	17
124	standard	146	10	18.568	100	6.950	32
125	standard	146	10	21.884	65	4.302	12
126	standard	146	10	21.443	67	10.253	100
127	standard	220	5	20.484	80	4.551	13
128	standard	220	5	18.733	100	5.516	20
129	standard	220	5	18.133	100	6.874	10
130	standard	220	5	22.877	58	2.427	0
131	standard	220	5	20.043	40	4.254	10
132	standard	220	5	20.898	73	6.633	33
133	standard	220	5	18.540	98	3.640	3
134	standard	220	10	16.189	95	9.170	93
135	standard	220	10	18.850	78	5.254	25
136	standard	220	10	18.092	90	7.743	70
137	standard	220	10	18.899	77	7.067	38
138	standard	220	10	21.726	75	4.557	58
139	standard	220	10	16.527	93	8.212	92
140	standard	220	10	17.120	98	8.350	87

Table B25. Strength Properties of the Shear Blocks Under Standard Conditions

Laminate	Shear Block	Length 1	Length 2	Width	Area	Load	Shear Strength	Wood Failure
		cm	cm	cm	cm^2	kN	MPa	%
1	1	4.484	4.464	4.801	21.479	37.6016	17.5060	80
	2	4.143	4.206	4.788	19.987	42.4325	21.2297	90
	3	4.112	4.051	4.740	19.346	36.6541	18.9462	70
2	1	4.128	4.039	5.088	20.773	32.5128	15.6512	100
	2	4.275	4.241	5.144	21.899	34.5234	15.7643	100
	3	4.192	4.158	5.118	21.369	33.7361	15.7873	90
3	1	4.313	4.304	5.050	21.756	47.4324	21.8019	100
	2	4.276	4.209	5.053	21.438	52.0142	24.2618	15
	3	4.174	4.149	5.071	21.105	38.6737	18.3242	60
4	1	4.036	4.009	5.119	20.594	41.5340	20.1678	95
	2	4.078	4.086	5.072	20.704	42.2501	20.4061	60
	3	4.120	4.131	5.132	21.173	34.6213	16.3515	50
5	1	4.281	4.239	5.130	21.853	40.5820	18.5702	70
	2	4.053	4.053	5.137	20.819	38.1755	18.3369	100
	3	4.276	4.262	5.135	21.920	31.7121	14.4668	100
6	1	4.238	4.251	5.130	21.771	42.0411	19.3099	80
	2	4.296	4.342	5.097	22.013	41.5206	18.8614	50
	3	4.155	4.172	5.146	21.427	36.4451	17.0090	60
7	1	3.838	3.825	5.131	19.659	32.8909	16.7303	15
	2	3.990	4.006	5.093	20.360	42.0944	20.6743	65
	3	3.887	3.903	5.144	20.034	34.0474	16.9942	30
8	1	4.143	4.141	5.166	21.400	42.5482	19.8824	95
	2	3.999	4.042	5.141	20.671	36.2360	17.5297	90
	3	4.301	4.281	5.114	21.947	41.4227	18.8736	90
9	1	4.304	4.326	5.103	22.018	48.6468	22.0938	40
	2	4.131	4.177	5.061	21.024	45.6131	21.6953	30
	3	4.308	4.364	5.034	21.828	33.7183	15.4473	15
10	1	4.115	4.128	5.103	21.030	38.1977	18.1635	100
	2	4.210	4.237	5.135	21.685	39.1719	18.0634	80
	3	4.346	4.326	5.126	22.224	43.7181	19.6713	95
11	1	4.398	4.474	5.108	22.659	36.6141	16.1582	30
	2	4.260	4.290	5.053	21.602	43.3533	20.0687	50
	3	4.177	4.205	5.067	21.237	32.8820	15.4831	80
12	1	4.406	4.373	5.175	22.715	42.9307	18.8996	80
	2	4.108	4.130	5.135	21.151	37.8863	17.9123	40
	3	4.255	4.233	5.174	21.957	38.9851	17.7550	100
13	1	4.455	4.442	4.801	21.357	46.9298	21.9736	100
	2	3.984	3.981	4.832	19.246	43.0375	22.3616	60
	3	3.827	3.777	4.854	18.453	37.2057	20.1616	70
14	1	4.190	4.173	5.122	21.417	31.2895	14.6093	50
	2	3.961	3.959	5.146	20.378	26.7477	13.1258	50
	3	4.063	4.032	5.154	20.859	25.3821	12.1680	30

Table B25. Continued

15	1	3.988	4.023	5.077	20.338	42.0099	20.6554	40
	2	4.135	4.129	5.140	21.237	44.9325	21.1574	95
	3	4.182	4.191	5.108	21.385	44.6567	20.8822	95
16	1	4.119	4.145	5.159	21.316	38.0732	17.8613	100
	2	4.288	4.228	5.126	21.824	38.7849	17.7717	100
	3	4.324	4.288	5.187	22.334	37.1835	16.6489	100
17	1	4.404	4.374	5.053	22.180	51.9920	23.4409	100
	2	4.337	4.295	5.130	22.140	36.5785	16.5216	90
	3	3.928	3.936	5.085	19.994	29.8126	14.9105	40
18	1	4.034	4.041	5.085	20.530	39.6479	19.3117	50
	2	3.936	3.915	5.098	20.012	31.3695	15.6754	60
	3	3.863	3.886	5.127	19.866	37.6684	18.9610	85
19	1	4.162	4.172	5.122	21.342	48.8514	22.8891	95
	2	3.947	3.967	5.141	20.344	45.1504	22.1927	90
	3	4.385	4.397	5.109	22.435	50.0614	22.3139	100
20	1	4.134	4.121	5.189	21.419	38.3134	17.8877	100
	2	4.161	4.161	5.175	21.532	40.5464	18.8307	45
	3	4.388	4.382	5.178	22.703	48.7313	21.4644	100
21	1	4.261	4.238	5.090	21.630	24.2389	11.2059	40
	2	4.008	4.016	5.056	20.284	23.8608	11.7633	30
	3	4.201	4.171	5.072	21.233	12.9935	6.1195	10
22	1	3.886	3.853	5.151	19.933	40.8712	20.5037	70
	2	3.993	3.984	5.128	20.454	48.6602	23.7900	50
	3	4.060	4.009	5.141	20.743	42.3258	20.4048	20
23	1	4.337	4.340	5.126	22.237	26.0227	11.7022	5
	2	4.112	4.105	5.180	21.283	38.3934	18.0391	60
	3	4.241	4.235	5.174	21.927	28.0378	12.7865	10
24	1	4.168	4.171	5.088	21.212	43.4823	20.4982	60
	2	4.324	4.337	5.161	22.352	51.0800	22.8522	50
	3	3.900	3.920	5.055	19.765	30.9959	15.6818	5
25	1	4.478	4.479	5.081	22.757	42.5170	18.6826	30
	2	3.995	3.954	5.123	20.362	31.8811	15.6570	80
	3	4.117	4.111	5.114	21.041	31.1872	14.8218	100
26	1	4.468	4.469	5.145	22.989	40.6443	17.6793	30
	2	4.220	4.199	5.138	21.630	45.7109	21.1330	90
	3	4.290	4.261	5.151	22.023	45.1371	20.4948	70
27	1	4.041	4.055	5.067	20.513	25.0752	12.2238	40
	2	4.301	4.277	5.123	21.975	13.1092	5.9653	15
	3	4.522	4.511	5.057	22.842	24.3812	10.6738	40
28	1	4.178	4.180	5.088	21.261	49.5320	23.2969	100
	2	3.938	3.915	5.083	19.958	49.4030	24.7527	60
	3	4.014	4.060	5.053	20.401	38.6070	18.9241	50

Table B25. Continued

29	1	4.276	4.266	5.192	22.174	46.8052	21.1078	50
	2	3.832	3.821	5.173	19.793	47.2945	23.8937	65
	3	4.007	3.951	5.118	20.364	41.8631	20.5566	95
30	1	3.787	3.754	5.151	19.423	39.7413	20.4607	100
	2	4.688	4.680	5.187	24.293	53.7357	22.1193	100
	3	4.227	4.191	5.140	21.632	49.7011	22.9755	100
31	1	4.130	4.092	5.182	21.302	39.5456	18.5644	95
	2	4.060	4.105	5.140	20.982	37.8018	18.0157	100
	3	3.948	3.946	5.108	20.162	35.9202	17.8156	100
32	1	4.028	3.975	5.128	20.522	43.2688	21.0837	80
	2	4.205	4.173	5.147	21.563	47.9529	22.2386	60
	3	4.211	4.194	5.226	21.962	50.3594	22.9298	30
33	1	4.322	4.313	5.160	22.278	49.6744	22.2975	65
	2	4.327	4.290	5.118	22.051	57.2232	25.9497	100
	3	4.355	4.321	5.173	22.438	42.9797	19.1549	70
34	1	4.001	3.938	5.084	20.180	51.2135	25.3784	70
	2	4.162	4.158	5.100	21.217	42.8507	20.1963	30
	3	4.065	4.056	5.103	20.722	49.1139	23.7012	60
35	1	3.816	3.832	5.104	19.518	39.2564	20.1126	90
	2	4.154	4.162	5.144	21.387	34.1942	15.9884	100
	3	3.969	3.978	5.144	20.436	33.5670	16.4251	100
36	1	4.120	4.121	5.183	21.356	32.8019	15.3593	30
	2	4.331	4.340	5.173	22.424	42.4637	18.9360	95
	3	4.256	4.285	5.097	21.764	42.1790	19.3798	100
37	1	4.361	4.341	5.163	22.462	57.5168	25.6054	85
	2	4.050	4.032	5.150	20.811	55.9065	26.8631	100
	3	4.020	4.018	5.062	20.345	47.3879	23.2922	100
38	1	4.288	4.228	5.160	21.970	35.4042	16.1148	40
	2	4.168	4.128	5.178	21.477	37.8152	17.6074	65
	3	4.011	3.989	5.097	20.385	49.0472	24.0596	80
39	1	4.136	4.130	5.144	21.259	44.4120	20.8904	85
	2	3.880	3.871	5.121	19.845	36.2538	18.2686	80
	3	4.092	4.056	5.110	20.821	38.1399	18.3178	100
40	1	3.961	4.011	5.124	20.426	36.2449	17.7446	60
	2	4.135	4.121	5.146	21.244	42.1389	19.8358	80
	3	3.938	3.932	5.171	20.350	37.0456	18.2038	100
41	1	4.103	4.083	5.229	21.402	44.5988	20.8386	70
	2	4.133	4.122	5.174	21.356	40.0794	18.7673	100
	3	4.051	4.032	5.208	21.051	44.2919	21.0403	80
42	1	4.107	4.126	5.090	20.955	39.8881	19.0351	15
	2	4.007	4.069	5.144	20.769	23.7718	11.4455	5
	3	4.105	4.117	5.124	21.067	31.9968	15.1882	70

Table B25. Continued

43	1	4.168	4.181	5.110	21.334	42.6016	19.9689	100
	2	3.945	3.942	5.135	20.248	49.0516	24.2256	100
	3	4.462	4.464	5.105	22.784	46.1068	20.2359	60
44	1	4.436	4.416	5.166	22.866	45.4618	19.8815	90
	2	4.157	4.103	5.132	21.196	43.9049	20.7138	70
	3	4.289	4.295	5.185	22.256	48.9938	22.0138	100
45	1	4.064	4.133	5.173	21.199	38.6114	18.2133	70
	2	4.451	4.435	5.194	23.079	45.5463	19.7349	80
	3	4.032	4.008	5.187	20.851	43.5846	20.9022	100
46	1	4.106	4.092	5.155	21.130	47.0054	22.2458	100
	2	4.229	4.219	5.185	21.903	38.6292	17.6360	80
	3	4.267	4.258	5.164	22.012	40.5197	18.4076	100
47	1	4.274	4.279	5.204	22.255	49.1406	22.0806	90
	2	4.321	4.329	5.160	22.317	46.0223	20.6218	50
	3	3.957	3.910	5.168	20.329	43.2777	21.2888	90
48	1	4.139	4.133	5.113	21.146	40.3729	19.0920	100
	2	3.785	3.744	5.004	18.836	40.5642	21.5355	95
	3	4.053	4.056	5.057	20.504	34.5768	16.8631	100
49	1	4.185	4.196	5.109	21.409	45.1015	21.0658	90
	2	4.319	4.354	5.069	21.979	36.9967	16.8321	100
	3	4.208	4.205	5.099	21.448	36.8143	17.1643	100
50	1	3.904	3.923	5.203	20.363	44.2830	21.7468	100
	2	4.079	4.102	5.103	20.874	36.3561	17.4166	95
	3	4.335	4.342	5.063	21.967	40.1105	18.2591	95
51	1	3.994	3.990	5.146	20.544	41.4272	20.1645	100
	2	4.275	4.293	5.145	22.039	43.2866	19.6409	95
	3	4.178	4.181	5.116	21.381	40.3151	18.8554	90
52	1	3.848	3.849	4.968	19.121	28.6828	15.0001	90
	2	4.063	4.041	4.948	20.049	43.7581	21.8256	100
	3	4.280	4.227	4.928	20.958	46.1291	22.0097	60
53	1	4.280	4.260	5.187	22.146	38.5313	17.3987	100
	2	4.096	4.116	5.122	21.030	50.6041	24.0623	100
	3	4.163	4.174	5.144	21.442	39.2208	18.2912	90
54	1	4.190	4.162	5.184	21.648	40.9957	18.9374	100
	2	4.144	4.167	5.119	21.273	46.2937	21.7611	100
	3	4.089	4.025	5.149	20.888	35.1417	16.8237	100
55	1	3.965	3.978	5.085	20.194	38.6025	19.1152	90
	2	4.204	4.335	4.964	21.194	40.2217	18.9779	60
	3	3.816	3.801	5.119	19.498	43.3622	22.2386	50
56	1	4.171	4.166	5.184	21.608	36.4584	16.8722	90
	2	3.807	3.796	5.204	19.786	30.2619	15.2943	100
	3	4.176	4.115	5.164	21.405	37.1346	17.3479	40

Table B25. Continued

57	1	4.026	4.050	5.083	20.523	44.3631	21.6158	100
	2	4.003	4.039	5.103	20.518	47.8061	23.2996	100
	3	4.100	4.082	5.084	20.796	53.0462	25.5073	85
58	1	4.135	4.167	5.185	21.525	40.1550	18.6551	100
	2	4.498	4.514	5.208	23.468	37.1168	15.8155	100
	3	4.448	4.408	5.119	22.668	45.5508	20.0946	100
59	1	4.148	4.158	5.147	21.376	37.0723	17.3425	90
	2	4.148	4.117	5.168	21.356	37.3347	17.4821	95
	3	4.345	4.356	5.142	22.371	43.0330	19.2361	85
60	1	4.186	4.177	5.178	21.651	44.6478	20.6214	100
	2	4.100	4.078	5.202	21.269	38.4869	18.0946	85
	3	4.208	4.159	5.102	21.342	38.9851	18.2666	75
61	1	4.382	4.338	5.163	22.508	38.6070	17.1521	95
	2	4.089	3.999	5.109	20.663	36.1426	17.4910	90
	3	4.114	4.125	5.141	21.177	41.1558	19.4340	90
62	1	4.379	4.318	5.069	22.041	36.7253	16.6623	100
	2	4.153	4.134	5.211	21.590	45.3640	21.0109	100
	3	4.411	4.406	5.180	22.836	43.8738	19.2124	85
63	1	4.225	4.219	5.095	21.513	51.4893	23.9340	90
	2	4.111	4.098	5.093	20.904	46.9476	22.4586	95
	3	4.091	4.081	5.155	21.061	51.8229	24.6058	40
64	1	3.874	3.844	5.079	19.598	43.6425	22.2682	80
	2	4.415	4.384	5.022	22.091	51.4092	23.2708	25
	3	4.171	4.167	5.067	21.124	43.4601	20.5730	60
65	1	4.152	4.114	5.217	21.560	49.0427	22.7464	100
	2	4.040	4.051	5.156	20.860	46.9876	22.5250	65
	3	4.016	3.965	5.177	20.656	49.2829	23.8584	65
66	1	4.359	4.347	5.154	22.433	45.2661	20.1776	100
	2	4.307	4.256	5.160	22.091	44.8880	20.3194	100
	3	4.340	4.366	5.212	22.688	52.5791	23.1747	70
67	1	4.148	4.139	5.105	21.154	40.5954	19.1905	60
	2	4.383	4.350	5.121	22.358	51.0578	22.8361	90
	3	4.315	4.351	5.077	22.002	49.6077	22.5467	100
68	1	4.172	4.121	5.156	21.380	41.4227	19.3738	90
	2	4.070	4.092	5.159	21.054	40.6487	19.3070	95
	3	4.110	4.116	5.194	21.364	42.5259	19.9055	90
69	1	4.147	4.114	5.151	21.274	39.3365	18.4898	95
	2	4.154	4.169	5.102	21.232	43.2644	20.3769	90
	3	4.262	4.267	5.099	21.746	45.3906	20.8730	40
70	1	4.168	4.168	5.093	21.227	38.2422	18.0155	100
	2	4.116	4.130	5.146	21.217	38.0020	17.9105	95
	3	4.139	4.120	5.141	21.229	40.0927	18.8854	100

Table B25.   Continued

	1	3.956	3.960	5.109	20.222	36.1248	17.8638	100
1	2	4.314	4.337	5.093	22.029	42.1478	19.1325	100
	3	4.013	3.998	5.155	20.648	36.1115	17.4884	95
	1	4.355	4.337	5.182	22.519	43.9005	19.4946	65
72	2	4.103	4.096	5.177	21.221	41.1470	19.3890	70
	3	4.191	4.169	5.179	21.650	40.5375	18.7241	90
	1	4.115	4.145	5.085	21.002	45.1549	21.5004	80
73	2	4.204	4.155	5.062	21.158	46.7340	22.0879	100
	3	4.111	4.130	5.057	20.838	37.8285	18.1533	95
	1	4.025	4.016	5.097	20.489	47.2812	23.0761	70
74	2	4.046	4.031	5.105	20.619	45.0704	21.8587	85
	3	3.875	3.868	5.099	19.741	42.8017	21.6808	80
	1	4.120	4.153	5.147	21.291	49.6432	23.3159	95
75	2	4.144	4.140	5.188	21.489	37.5305	17.4647	70
	3	4.380	4.401	5.166	22.682	44.1362	19.4581	15
	1	4.131	4.079	5.095	20.917	30.9692	14.8053	100
76	2	4.058	4.055	5.080	20.606	39.5811	19.2079	95
	3	4.639	4.613	5.163	23.882	48.8915	20.4719	100
	1	4.214	4.216	5.177	21.820	39.4166	18.0644	95
77	2	4.215	4.208	5.174	21.789	40.4041	18.5428	100
	3	4.251	4.246	5.182	22.012	37.5038	17.0374	100
	1	4.064	4.023	5.102	20.629	45.8132	22.2076	60
78	2	4.121	4.081	5.141	21.082	41.9521	19.8990	70
	3	4.152	4.140	5.136	21.293	48.4822	22.7688	90
	1	4.194	4.195	5.093	21.360	42.4992	19.8966	55
79	2	4.166	4.209	5.095	21.335	49.6833	23.2871	75
	3	4.215	4.196	5.027	21.140	44.9947	21.2837	100
	1	3.932	3.942	5.100	20.080	37.1435	18.4975	40
80	2	4.130	4.158	5.017	20.788	35.7156	17.1802	70
	3	4.159	4.136	5.127	21.266	37.3392	17.5580	90
	1	4.086	4.112	5.131	21.031	42.3925	20.1570	75
81	2	4.018	4.025	5.184	20.848	45.1237	21.6440	100
	3	4.221	4.219	5.154	21.750	41.1781	18.9326	100
	1	4.121	4.107	4.858	19.986	42.0144	21.0220	100
82	2	4.112	4.135	4.793	19.765	40.3507	20.4152	100
	3	4.001	3.981	4.836	19.301	36.8499	19.0919	70
	1	4.248	4.272	5.168	22.015	40.9423	18.5970	100
83	2	4.227	4.252	5.147	21.821	39.0874	17.9126	100
	3	4.072	4.050	5.211	21.160	36.5874	17.2904	90
	1	4.020	4.002	5.132	20.583	34.1720	16.6018	80
84	2	4.261	4.002	5.135	21.213	42.2145	19.9003	100
	3	3.926	3.960	5.079	20.024	37.0589	18.5070	100

Table B25. Continued

85	1	4.119	4.140	5.211	21.518	44.4120	20.6396	100
	2	4.354	4.309	5.177	22.421	42.8551	19.1133	100
	3	4.290	4.296	5.144	22.082	42.9886	19.4672	60
86	1	4.298	4.308	5.110	21.989	46.8719	21.3156	80
	2	4.134	4.098	5.062	20.836	53.1841	25.5241	100
	3	4.205	4.224	5.112	21.543	55.1058	25.5785	100
87	1	4.247	4.272	5.174	22.039	40.9334	18.5729	85
	2	4.136	4.166	5.164	21.435	44.7501	20.8768	90
	3	3.832	3.871	5.117	19.706	33.7672	17.1349	100
88	1	4.135	4.108	5.102	21.028	31.1427	14.8101	80
	2	4.322	4.293	5.069	21.831	39.8347	18.2463	100
	3	4.195	4.201	5.083	21.336	30.2664	14.1851	100
89	1	3.894	3.905	5.192	20.245	46.2269	22.8329	90
	2	4.110	4.122	5.213	21.459	44.7768	20.8663	85
	3	4.003	3.975	5.175	20.644	43.7047	21.1699	100
90	1	4.249	4.326	5.056	21.677	41.2137	19.0122	65
	2	4.026	4.039	5.130	20.684	37.9797	18.3620	70
	3	4.294	4.312	5.079	21.853	38.6559	17.6891	100
91	1	4.434	4.404	5.170	22.847	45.4574	19.8963	100
	2	4.185	4.133	5.116	21.274	39.3053	18.4758	100
	3	4.053	4.061	5.164	20.950	39.0207	18.6256	100
92	1	3.959	3.981	5.089	20.203	44.5010	22.0266	100
	2	4.229	4.265	5.113	21.714	44.9102	20.6819	100
	3	4.041	4.068	5.121	20.762	37.5260	18.0745	100
93	1	4.448	4.437	5.124	22.765	44.4698	19.5339	95
	2	4.201	4.176	5.130	21.485	35.5332	16.5385	100
	3	4.239	4.238	5.088	21.565	42.6638	19.7840	100
94	1	4.280	4.251	5.102	21.760	48.0908	22.1004	100
	2	4.086	4.068	5.094	20.767	33.1978	15.9859	100
	3	4.338	4.310	5.085	21.990	41.8587	19.0353	100
95	1	4.122	4.148	5.126	21.195	48.2465	22.7623	100
	2	3.932	3.956	5.222	20.596	41.5429	20.1696	100
	3	4.074	4.065	5.133	20.891	46.5072	22.2612	100
96	1	4.067	4.036	5.163	20.915	43.8515	20.9662	100
	2	3.910	3.895	5.138	20.054	42.3836	21.1346	80
	3	4.055	4.092	5.133	20.911	48.9982	23.4317	100
97	1	4.061	4.087	5.132	20.909	39.9815	19.1215	100
	2	4.074	4.042	5.138	20.853	41.5784	19.9383	60
	3	3.912	3.909	5.144	20.113	37.5082	18.6487	100
98	1	4.144	4.114	5.156	21.289	39.3988	18.5065	100
	2	4.164	4.140	5.157	21.415	42.8907	20.0279	85
	3	4.481	4.501	5.166	23.201	52.8683	22.7870	50

Table B25. Continued

99	1	4.081	4.068	5.098	20.769	40.1327	19.3229	95
	2	4.006	4.018	5.089	20.416	42.5615	20.8465	100
	3	4.241	4.241	5.130	21.752	39.3231	18.0777	100
100	1	4.028	4.022	5.085	20.469	42.0277	20.5323	100
	2	4.238	4.234	5.114	21.665	41.7920	19.2902	95
	3	4.239	4.223	5.018	21.230	48.4066	22.8005	90
101	1	3.866	3.858	5.178	19.997	46.0979	23.0521	95
	2	4.097	4.108	5.179	21.248	48.9538	23.0385	50
	3	4.021	4.036	5.187	20.894	49.7322	23.8015	100
102	1	4.420	4.390	5.156	22.713	49.4431	21.7682	90
	2	4.272	4.270	5.157	22.028	41.4717	18.8268	100
	3	4.096	4.059	5.146	20.982	45.5152	21.6920	95
103	1	4.001	3.989	5.102	20.380	39.6523	19.4564	40
	2	4.201	4.223	5.090	21.440	44.7101	20.8537	45
	3	3.861	3.865	5.132	19.824	45.5108	22.9574	85
104	1	4.026	4.022	5.098	20.513	44.6255	21.7539	100
	2	4.081	4.069	5.123	20.876	47.4458	22.7272	80
	3	4.026	3.998	5.163	20.712	47.3835	22.8772	40
105	1	4.144	4.117	5.170	21.356	32.0768	15.0196	100
	2	4.200	4.196	5.150	21.619	40.3596	18.6683	80
	3	4.308	4.251	5.164	22.097	43.6603	19.7578	95
106	1	3.992	3.993	5.110	20.402	42.1167	20.6428	100
	2	3.843	3.865	5.067	19.528	38.1132	19.5165	100
	3	4.041	4.064	5.063	20.520	36.6364	17.8536	60
107	1	4.023	3.990	5.154	20.650	43.4823	21.0565	100
	2	4.327	4.318	5.118	22.123	44.8569	20.2761	100
	3	4.068	4.083	5.075	20.682	37.1435	17.9586	100
108	1	4.338	4.360	4.812	20.928	41.0313	19.6056	95
	2	4.295	4.275	5.215	22.345	44.0384	19.7085	85
	3	4.425	4.403	4.826	21.301	45.3729	21.3001	85
109	1	4.242	4.249	5.098	21.643	35.8268	16.5531	90
	2	4.260	4.258	5.070	21.592	46.6317	21.5963	85
	3	4.305	4.318	5.071	21.865	31.3028	14.3163	90
110	1	4.023	4.031	5.063	20.392	45.1593	22.1458	100
	2	4.074	4.083	5.145	20.983	44.5188	21.2158	85
	3	3.818	3.805	5.122	19.521	36.5963	18.7469	100
111	1	4.166	4.124	5.179	21.465	35.2707	16.4312	100
	2	4.388	4.373	5.203	22.791	41.2937	18.1180	90
	3	4.284	4.291	5.123	21.966	48.4422	22.0532	20
112	1	4.087	4.190	5.091	21.070	37.6239	17.8565	100
	2	4.277	4.241	5.159	21.971	51.5916	23.4815	95
	3	4.100	4.103	5.124	21.018	40.0037	19.0330	90

Table B25. Continued

113	1	4.103	4.074	5.085	20.792	45.0659	21.6746	50
	2	4.260	4.241	5.144	21.860	50.3238	23.0204	100
	3	4.017	4.025	5.088	20.456	47.3168	23.1302	85
114	1	4.143	4.126	5.034	20.814	42.1567	20.2536	70
	2	4.215	4.228	5.088	21.477	49.7055	23.1429	100
	3	4.112	4.139	5.024	20.727	46.2937	22.3341	30
115	1	4.065	4.032	5.062	20.496	57.1653	27.8909	90
	2	4.232	4.192	5.105	21.504	55.8620	25.9774	90
	3	4.067	4.047	5.028	20.398	42.2190	20.6969	100
116	1	4.020	4.026	5.072	20.405	40.5642	19.8794	85
	2	4.035	4.039	5.107	20.614	41.6541	20.2063	80
	3	4.128	4.140	5.044	20.853	43.0375	20.6382	30
117	1	4.200	4.202	5.127	21.539	37.6550	17.4817	95
	2	4.089	4.083	5.098	20.831	34.9504	16.7781	80
	3	4.355	4.368	5.072	22.122	48.9315	22.1190	60
118	1	4.272	4.244	5.070	21.589	41.3694	19.1620	30
	2	4.042	4.041	5.100	20.614	43.4111	21.0584	90
	3	3.799	3.830	5.033	19.198	37.2013	19.3772	60
119	1	4.227	4.241	5.131	21.721	42.1167	19.3891	100
	2	4.084	4.082	5.117	20.892	39.2698	18.7960	100
	3	4.161	4.130	5.166	21.416	40.2751	18.8058	40
120	1	4.171	4.172	5.156	21.508	36.0670	16.7687	100
	2	4.101	4.115	5.137	21.102	42.5927	20.1834	100
	3	4.039	4.041	5.116	20.666	38.8027	18.7756	80
121	1	3.997	3.973	5.097	20.308	43.0108	21.1792	100
	2	4.023	4.002	5.105	20.486	40.0482	19.5490	75
	3	4.100	4.098	5.091	20.869	39.6968	19.0212	100
122	1	4.220	4.238	5.095	21.548	45.6131	21.1675	100
	2	3.990	4.004	5.105	20.408	40.5820	19.8851	100
	3	3.962	3.936	5.147	20.327	43.8471	21.5705	85
123	1	4.199	4.192	5.029	21.100	47.2723	22.4039	70
	2	4.180	4.202	5.062	21.216	37.0589	17.4674	100
	3	4.067	4.098	5.051	20.619	38.0109	18.4342	80
124	1	4.350	4.345	5.127	22.288	42.8418	19.2215	100
	2	4.188	4.205	5.107	21.431	39.5545	18.4562	100
	3	4.356	4.351	5.144	22.393	40.3418	18.0155	100
125	1	3.344	3.373	5.017	16.848	41.6140	24.6993	50
	2	3.992	4.008	5.033	20.131	41.7831	20.7549	55
	3	4.067	4.102	5.036	20.567	41.5562	20.2052	90
126	1	4.161	4.102	5.076	20.971	45.8800	21.8771	100
	2	4.082	4.119	5.066	20.772	42.6549	20.5348	50
	3	4.087	4.068	5.079	20.708	45.3773	21.9129	50

Table B25. Continued

127	1	4.341	4.501	5.061	22.374	46.9965	21.0048	85
	2	4.242	4.271	5.090	21.666	46.5828	21.5003	65
	3	3.983	4.011	5.110	20.425	38.7048	18.9494	90
128	1	3.887	3.899	5.062	19.707	35.8490	18.1908	100
	2	4.468	4.483	5.058	22.639	36.3917	16.0747	100
	3	4.135	4.149	5.075	21.021	46.1291	21.9441	100
129	1	4.596	4.569	5.077	23.269	41.2181	17.7135	100
	2	4.256	4.242	5.126	21.778	43.0953	19.7881	100
	3	4.324	4.315	5.110	22.077	37.3036	16.8969	100
130	1	4.120	4.050	5.182	21.167	52.0453	24.5880	60
	2	4.023	4.050	5.127	20.696	45.3061	21.8908	30
	3	4.257	4.234	5.152	21.875	48.4778	22.1609	85
131	1	3.952	3.967	5.095	20.176	39.4966	19.5753	30
	2	4.163	4.143	5.121	21.266	40.0126	18.8154	60
	3	3.880	3.910	5.100	19.866	43.1843	21.7372	30
132	1	4.195	4.225	5.133	21.612	45.2305	20.9285	70
	2	3.844	3.868	5.072	19.561	39.9637	20.4301	100
	3	4.092	4.088	5.135	21.001	44.8035	21.3339	50
133	1	4.039	4.008	5.199	20.919	38.1577	18.2404	100
	2	4.202	4.205	5.156	21.675	37.3926	17.2511	100
	3	4.346	4.346	5.192	22.563	45.4129	20.1268	95
134	1	4.397	4.413	5.118	22.545	43.5579	19.3200	90
	2	4.167	4.112	5.155	21.339	28.4070	13.3119	100
	3	4.328	4.284	5.124	22.066	35.1595	15.9339	95
135	1	4.500	4.501	5.182	23.318	40.1194	17.2047	100
	2	3.881	3.862	5.188	20.086	37.3748	18.6074	40
	3	4.202	4.168	5.104	21.362	44.2875	20.7313	95
136	1	3.985	3.995	5.067	20.220	34.8659	17.2428	75
	2	4.390	4.428	5.074	22.372	40.8712	18.2686	100
	3	4.069	4.045	5.145	20.872	39.1852	18.7734	95
137	1	4.406	4.418	5.168	22.799	36.6141	16.0589	30
	2	4.266	4.263	5.166	22.033	46.4671	21.0897	100
	3	4.298	4.272	5.102	21.860	42.7172	19.5408	100
138	1	4.370	4.389	5.015	21.965	50.9688	23.2045	65
	2	4.069	4.082	5.085	20.724	40.2795	19.4360	100
	3	4.110	4.139	5.061	20.873	47.0232	22.5279	60
139	1	4.126	4.108	5.131	21.125	34.3811	16.2746	100
	2	4.390	4.366	5.152	22.559	38.8071	17.2024	100
	3	4.255	4.235	5.116	21.715	34.9816	16.1088	80
140	1	4.110	4.130	5.098	21.002	32.2370	15.3491	95
	2	4.224	4.230	5.194	21.957	36.4451	16.5979	100
	3	4.036	3.995	5.152	20.691	40.1550	19.4070	100

Table B26. Strength Properties of the Shear Blocks for the Water-soaked Condition

Laminate	Shear Block	Length 1	Length 2	Width	Area	Load	Shear Strength	Wood Failure
		cm	cm	cm	cm^2	kN	MPa	%
1	1	4.338	4.327	5.241	22.708	5.8184	2.5622	0
	2	4.116	4.106	5.235	21.521	6.4056	2.9764	0
	3	4.498	4.473	5.204	23.345	11.9304	5.1103	20
2	1	4.247	4.213	5.491	23.228	6.1209	2.6351	0
	2	4.307	4.318	5.455	23.522	6.1031	2.5946	0
	3	4.266	4.229	5.551	23.579	8.5942	3.6448	0
3	1	4.031	3.989	5.502	22.062	5.4892	2.4881	0
	2	4.056	4.049	5.532	22.419	8.7543	3.9047	0
	3	4.338	4.318	5.488	23.752	7.9402	3.3430	10
4	1	4.157	4.169	5.505	22.920	9.0167	3.9340	10
	2	3.975	3.979	5.494	21.850	9.6617	4.4218	30
	3	3.763	3.716	5.480	20.493	8.9233	4.3543	10
5	1	4.097	4.094	5.517	22.596	12.6199	5.5850	30
	2	4.374	4.418	5.551	24.404	12.9090	5.2897	40
	3	4.356	4.347	5.550	24.151	13.3894	5.5439	45
6	1	4.026	4.016	5.559	22.351	7.0194	3.1405	0
	2	4.394	4.398	5.622	24.716	7.1262	2.8832	0
	3	4.058	4.078	5.507	22.400	5.0622	2.2598	0
7	1	4.073	4.079	5.499	22.415	12.4153	5.5388	0
	2	4.103	4.119	5.528	22.727	6.7614	2.9750	0
	3	3.909	3.890	5.589	21.796	8.2917	3.8042	0
8	1	4.199	4.178	5.456	22.852	11.4544	5.0124	50
	2	4.421	4.427	5.540	24.508	11.5034	4.6936	30
	3	4.087	4.086	5.569	22.756	10.9785	4.8243	30
9	1	3.844	3.884	5.484	21.189	8.1716	3.8564	60
	2	4.228	4.257	5.546	23.529	8.8922	3.7792	60
	3	4.274	4.336	5.447	23.448	11.1608	4.7598	40
10	1	4.355	4.352	5.481	23.863	9.8664	4.1345	10
	2	4.440	4.404	5.458	24.138	9.9020	4.1022	10
	3	4.164	4.180	5.508	22.979	10.8761	4.7330	20
11	1	4.129	4.155	5.080	21.042	5.6805	2.6996	0
	2	4.237	4.248	5.460	23.163	9.5372	4.1174	40
	3	4.206	4.271	5.507	23.341	7.9136	3.3904	5
12	1	4.256	4.216	5.616	23.790	8.8121	3.7041	5
	2	3.759	3.706	5.578	20.819	7.3264	3.5190	0
	3	4.055	4.044	5.634	22.813	13.0336	5.7131	25
13	1	3.952	3.954	5.267	20.819	12.9046	6.1985	60
	2	3.995	4.023	5.180	20.770	10.4135	5.0137	40
	3	4.092	4.083	5.302	21.673	12.2329	5.6442	40
14	1	4.144	4.083	5.472	22.511	7.2152	3.2051	0
	2	4.128	4.229	5.495	22.961	12.7311	5.5446	20
	3	4.084	4.056	5.471	22.270	8.3895	3.7672	15

Table B26. Continued

15	1	4.272	4.261	5.478	23.370	5.3291	2.2803	0
	2	4.290	4.282	5.528	23.696	11.1964	4.7250	5
	3	4.275	4.268	5.490	23.452	11.4767	4.8936	0
16	1	4.247	4.252	5.602	23.805	12.2818	5.1592	5
	2	4.464	4.440	5.546	24.691	12.3485	5.0011	15
	3	4.266	4.270	5.564	23.746	11.5745	4.8743	10
17	1	4.672	4.667	5.469	25.537	8.8966	3.4837	0
	2	4.408	4.380	5.593	24.577	13.4517	5.4732	5
	3	4.352	4.357	5.507	23.981	7.8824	3.2869	5
18	1	4.018	4.011	5.505	22.101	11.3210	5.1222	5
	2	4.192	4.102	5.566	23.085	14.6661	6.3530	40
	3	3.898	3.905	5.509	21.494	13.0959	6.0927	60
19	1	4.047	4.026	5.559	22.439	8.4740	3.7764	5
	2	4.168	4.194	5.571	23.294	7.7490	3.3266	20
	3	4.036	4.072	5.504	22.313	7.8068	3.4987	0
20	1	4.068	4.064	5.636	22.916	9.2258	4.0258	20
	2	4.086	4.065	5.635	22.965	9.6039	4.1819	15
	3	5.310	5.259	5.630	29.751	12.6332	4.2462	5
21	1	4.045	4.064	5.464	22.152	6.3033	2.8454	5
	2	4.105	4.120	5.422	22.295	11.1030	4.9799	15
	3	4.084	4.054	5.514	22.438	6.4234	2.8626	0
22	1	3.998	3.905	5.547	21.921	1.0543	0.4809	0
	2	4.247	4.218	5.479	23.188	10.3379	4.4583	0
	3	failed	failed	failed	failed	0.0000	0.0000	0
23	1	4.464	4.473	5.583	24.947	12.4286	4.9819	40
	2	4.290	4.293	5.605	24.051	7.6556	3.1830	10
	3	4.270	4.255	5.593	23.838	11.8147	4.9561	10
24	1	4.039	4.039	5.566	22.481	8.3539	3.7160	0
	2	4.210	4.213	5.545	23.351	8.9233	3.8213	0
	3	4.152	4.164	5.547	23.066	7.5621	3.2785	0
25	1	4.163	4.159	5.612	23.353	7.1974	3.0820	5
	2	4.103	4.130	5.571	22.936	8.9189	3.8885	15
	3	4.174	4.158	5.582	23.254	10.1778	4.3766	20
26	1	3.928	3.913	5.569	21.833	10.0132	4.5862	5
	2	4.474	4.467	5.588	24.981	9.5550	3.8249	5
	3	4.225	4.201	5.625	23.699	10.3157	4.3528	0
27	1	4.408	4.426	5.488	24.239	4.1458	1.7103	0
	2	3.920	3.947	5.512	21.682	5.4937	2.5337	0
	3	4.277	4.267	5.519	23.581	7.3887	3.1333	0
28	1	4.131	4.138	5.503	22.752	11.0229	4.8448	20
	2	4.088	4.126	5.508	22.622	12.0016	5.3051	5
	3	4.183	4.194	5.538	23.198	9.0212	3.8888	0

Table B26. Continued

29	1	4.153	4.191	5.613	23.419	13.2337	5.6508	60
	2	3.937	3.922	5.635	22.142	13.1270	5.9284	60
	3	4.087	4.053	5.655	23.015	12.6955	5.5160	60
30	1	4.143	4.168	5.597	23.258	13.2471	5.6957	65
	2	4.324	4.266	5.668	24.345	13.3761	5.4943	50
	3	4.268	4.352	5.596	24.119	17.4508	7.2351	85
31	1	4.028	4.027	5.613	22.610	16.5433	7.3168	60
	2	4.140	4.110	5.467	22.553	18.1269	8.0375	80
	3	3.800	3.802	5.535	21.038	15.7782	7.4998	85
32	1	3.976	4.011	5.589	22.321	20.3110	9.0994	40
	2	3.846	3.821	5.610	21.504	10.8495	5.0452	20
	3	3.905	3.879	5.638	21.941	13.3316	6.0761	25
33	1	4.152	4.158	5.641	23.439	13.8877	5.9250	50
	2	4.089	4.074	5.615	22.918	18.8920	8.2432	60
	3	4.298	4.270	5.563	23.829	18.6073	7.8087	70
34	1	4.042	3.992	5.513	22.146	16.6501	7.5182	50
	2	4.061	4.008	5.508	22.224	16.9748	7.6381	50
	3	3.981	3.941	5.513	21.838	12.9891	5.9478	30
35	1	4.125	4.120	5.503	22.685	19.8884	8.7670	60
	2	4.025	4.025	5.525	22.234	18.2203	8.1946	70
	3	4.126	4.168	5.493	22.779	12.8512	5.6415	60
36	1	4.025	4.018	5.635	22.661	8.4296	3.7198	20
	2	4.449	4.450	5.729	25.491	17.0282	6.6800	0
	3	4.077	4.083	5.509	22.477	19.1367	8.5137	75
37	1	4.032	4.008	5.500	22.113	21.2630	9.6157	40
	2	4.228	4.209	5.493	23.170	16.1652	6.9766	50
	3	4.274	4.249	5.411	23.061	20.7203	8.9849	50
38	1	4.162	4.191	5.500	22.972	18.5095	8.0574	50
	2	4.352	4.343	5.565	24.196	23.7362	9.8097	65
	3	4.016	4.082	5.587	22.619	19.3457	8.5526	30
39	1	4.195	4.148	5.528	23.060	21.2630	9.2204	100
	2	4.054	4.063	5.555	22.544	13.8476	6.1425	40
	3	4.155	4.130	5.545	22.971	19.2968	8.4005	90
40	1	4.141	4.159	5.686	23.598	22.2149	9.4137	65
	2	4.317	4.294	5.568	23.971	22.2238	9.2712	80
	3	4.220	4.209	5.582	23.524	16.9436	7.2026	50
41	1	4.214	4.210	5.618	23.665	10.7783	4.5545	20
	2	4.304	4.268	5.598	23.995	17.1705	7.1557	75
	3	4.442	4.432	5.738	25.461	17.5397	6.8887	65
42	1	4.294	4.305	5.469	23.513	12.5176	5.3236	0
	2	4.213	4.188	5.585	23.462	13.0425	5.5589	40
	3	4.035	4.037	5.493	22.169	10.6137	4.7875	15

Table B26. Continued

43	1	4.069	4.102	5.544	22.649	9.4616	4.1775	15
	2	4.303	4.271	5.566	23.863	7.0595	2.9583	25
	3	4.440	4.450	5.574	24.777	13.2916	5.3645	30
44	1	4.152	4.129	5.584	23.120	13.5229	5.8490	65
	2	4.249	4.215	5.577	23.602	13.6252	5.7729	60
	3	4.496	4.573	5.597	25.379	19.8262	7.8118	80
45	1	4.543	4.511	5.696	25.785	12.7622	4.9494	0
	2	4.267	4.258	5.697	24.286	16.6278	6.8466	10
	3	4.322	4.277	5.632	24.217	12.0727	4.9851	10
46	1	4.335	4.345	5.584	24.233	13.1181	5.4132	10
	2	4.117	4.121	5.644	23.249	8.4918	3.6526	15
	3	4.483	4.530	5.697	25.675	13.1047	5.1040	10
47	1	4.154	4.145	5.650	23.447	9.9776	4.2553	5
	2	4.115	4.139	5.648	23.307	16.2052	6.9528	60
	3	4.182	4.152	5.650	23.544	13.2738	5.6378	65
48	1	4.101	4.124	5.488	22.567	12.9713	5.7479	75
	2	4.194	4.228	5.476	23.059	13.4473	5.8317	70
	3	4.229	4.195	5.495	23.146	15.4979	6.6957	60
49	1	4.308	4.361	5.512	23.891	11.7836	4.9322	20
	2	4.140	4.136	5.511	22.804	12.9757	5.6900	65
	3	4.464	4.441	5.519	24.576	13.0291	5.3015	30
50	1	4.423	4.464	5.418	24.075	20.2399	8.4068	70
	2	4.134	4.141	5.605	23.190	13.3005	5.7355	70
	3	3.926	3.922	5.400	21.188	13.3405	6.2962	60
51	1	3.799	3.780	5.420	20.538	13.7275	6.6839	50
	2	3.915	3.904	5.504	21.520	10.7071	4.9754	10
	3	4.192	4.213	5.516	23.179	11.6724	5.0357	15
52	1	4.004	4.014	5.267	21.116	10.4491	4.9483	0
	2	4.288	4.241	5.450	23.237	12.9001	5.5514	20
	3	4.313	4.271	5.343	22.931	12.0994	5.2763	20
53	1	4.150	4.166	5.555	23.097	9.8263	4.2542	40
	2	4.329	4.336	5.571	24.139	20.3600	8.4343	60
	3	4.267	4.276	5.592	23.886	22.4640	9.4044	100
54	1	4.294	4.296	5.549	23.832	17.1082	7.1785	90
	2	4.081	4.106	5.542	22.686	17.3351	7.6413	90
	3	4.341	4.327	5.569	24.135	20.0441	8.3048	80
55	1	4.040	4.041	5.579	22.542	18.2826	8.1102	80
	2	4.214	4.262	5.455	23.117	16.6367	7.1967	80
	3	4.789	4.827	5.564	26.752	16.2275	6.0657	75
56	1	4.053	3.990	5.467	21.987	7.9180	3.6012	20
	2	4.507	4.470	5.584	25.066	13.1848	5.2599	20
	3	4.290	4.296	5.622	24.138	12.1662	5.0402	40

Table B26. Continued

57	1	4.209	4.168	5.526	23.144	25.2931	10.9282	100
	2	4.153	4.155	5.540	23.013	22.8510	9.9294	95
	3	4.249	4.238	5.646	23.962	21.6010	9.0147	90
58	1	4.289	4.281	5.594	23.972	19.6393	8.1926	100
	2	4.380	4.347	5.558	24.251	19.5682	8.0687	100
	3	4.375	4.368	5.521	24.133	18.2515	7.5628	100
59	1	4.411	4.780	5.599	25.732	22.7087	8.8249	100
	2	4.205	4.204	5.559	23.371	19.1723	8.2033	90
	3	4.200	4.218	5.570	23.444	21.2986	9.0848	90
60	1	4.428	4.442	5.690	25.236	21.0895	8.3567	90
	2	3.974	4.045	5.679	22.771	19.3190	8.4839	80
	3	4.154	4.145	5.668	23.521	18.9721	8.0660	80
61	1	4.275	4.270	5.635	24.074	19.5059	8.1023	85
	2	4.274	4.253	5.602	23.883	20.3333	8.5134	80
	3	4.216	4.182	5.626	23.625	18.3493	7.7666	75
62	1	4.282	4.274	5.495	23.509	19.9730	8.4958	95
	2	3.987	3.971	5.654	22.497	20.1286	8.9471	85
	3	4.342	4.260	5.358	23.045	18.7452	8.1342	95
63	1	4.514	4.469	5.448	24.470	20.1731	8.2438	30
	2	3.851	4.281	5.478	22.271	18.4116	8.2669	70
	3	4.182	4.201	5.500	23.056	20.9249	9.0757	70
64	1	4.027	4.022	5.542	22.306	18.5050	8.2960	0
	2	4.484	4.484	5.455	24.461	23.0423	9.4200	20
	3	4.390	4.366	5.434	23.793	19.9996	8.4055	65
65	1	4.219	4.249	5.621	23.800	18.1536	7.6273	90
	2	4.281	4.272	5.643	24.132	22.0859	9.1520	85
	3	3.983	3.967	5.613	22.314	20.8315	9.3355	90
66	1	4.646	4.629	5.716	26.509	26.8545	10.1303	80
	2	4.326	4.317	5.563	24.037	22.9978	9.5675	100
	3	3.959	3.929	5.535	21.829	21.3386	9.7754	100
67	1	4.026	4.026	5.523	22.236	21.5210	9.6783	70
	2	4.202	4.115	5.531	23.001	22.1259	9.6195	90
	3	4.458	4.463	5.481	24.448	19.7372	8.0730	15
68	1	4.044	4.018	5.634	22.709	20.1375	8.8673	80
	2	3.950	3.950	5.624	22.211	20.4356	9.2004	95
	3	4.229	4.204	5.664	23.883	17.2283	7.2137	80
69	1	4.201	4.190	5.485	23.013	23.6784	10.2892	100
	2	3.894	3.914	5.526	21.572	18.7274	8.6810	60
	3	4.086	4.065	5.495	22.396	23.3003	10.4038	100
70	1	4.087	4.053	5.573	22.680	24.0699	10.6129	100
	2	4.173	4.185	5.561	23.240	22.9667	9.8820	100
	3	4.041	4.025	5.480	22.100	19.9196	9.0131	100

Table B26. Continued

71	1	3.948	3.950	5.499	21.716	20.6535	9.5105	90
	2	4.178	4.213	5.486	23.018	21.0583	9.1485	100
	3	3.899	3.903	5.500	21.456	18.9988	8.8547	90
72	1	3.942	3.918	5.601	22.011	17.0015	7.7240	60
	2	4.328	4.357	5.652	24.543	21.0183	8.5637	60
	3	4.064	4.055	5.644	22.912	22.2416	9.7074	100
73	1	4.167	4.133	5.488	22.772	23.3626	10.2590	90
	2	4.347	4.329	5.547	24.066	18.2781	7.5948	70
	3	4.229	4.227	5.433	22.970	20.7114	9.0165	85
74	1	3.995	3.975	5.608	22.351	22.2861	9.9710	80
	2	4.023	4.031	5.507	22.176	22.4729	10.1335	95
	3	4.051	4.035	5.556	22.464	22.1215	9.8473	95
75	1	3.989	4.011	5.654	22.615	13.1270	5.8044	60
	2	4.208	4.208	5.606	23.586	18.6029	7.8870	80
	3	4.124	4.121	5.650	23.293	16.9703	7.2856	80
76	1	4.149	4.194	5.509	22.981	21.5699	9.3859	80
	2	4.324	4.357	5.508	23.909	17.6999	7.4028	90
	3	4.270	4.305	5.480	23.496	21.1696	9.0098	100
77	1	3.954	3.937	5.612	22.141	18.2114	8.2250	95
	2	4.168	4.130	5.561	23.074	19.5192	8.4591	100
	3	4.202	4.229	5.612	23.659	20.0085	8.4568	100
78	1	4.115	4.068	5.583	22.841	22.2371	9.7353	30
	2	3.987	4.013	5.514	22.057	22.3928	10.1523	95
	3	4.380	4.326	5.578	24.280	23.8163	9.8089	50
79	1	4.227	4.168	5.467	22.948	23.8875	10.4091	95
	2	4.183	4.166	5.386	22.484	22.5485	10.0285	100
	3	4.221	4.173	5.512	23.135	23.7451	10.2636	95
80	1	4.131	4.119	5.527	22.799	21.2941	9.3399	90
	2	4.258	4.234	5.531	23.485	19.7194	8.3963	50
	3	4.077	4.081	5.547	22.625	21.8590	9.6611	100
81	1	4.008	4.047	5.559	22.390	22.6153	10.1006	100
	2	4.251	4.270	5.618	23.936	25.0796	10.4776	90
	3	4.293	4.285	5.641	24.195	23.3804	9.6633	100
82	1	4.111	4.112	5.284	21.728	22.6197	10.4103	100
	2	4.224	4.224	5.208	22.000	22.4373	10.1987	100
	3	4.180	4.150	5.227	21.772	22.1081	10.1544	100
83	1	4.190	4.172	5.542	23.171	18.0602	7.7940	100
	2	4.159	4.154	5.544	23.043	17.9000	7.7680	100
	3	4.268	4.265	5.611	23.939	19.0788	7.9696	85
84	1	4.017	3.985	5.549	22.201	21.0094	9.4632	50
	2	4.112	4.069	5.594	22.885	20.2221	8.8364	95
	3	4.312	4.286	5.491	23.608	20.3733	8.6298	95

Table B26. Continued

85	1	4.258	4.255	5.545	23.601	21.7211	9.2033	90
	2	4.232	4.216	5.555	23.464	24.9506	10.6333	100
	3	4.174	4.148	5.624	23.401	23.3759	9.9893	95
86	1	4.053	4.028	5.584	22.563	21.6811	9.6090	95
	2	4.134	4.092	5.552	22.837	22.2905	9.7607	95
	3	4.379	4.346	5.521	24.084	22.5886	9.3790	95
87	1	4.134	4.147	5.621	23.272	21.8813	9.4022	95
	2	3.957	3.948	5.594	22.114	18.4116	8.3257	70
	3	4.322	4.337	5.659	24.501	22.1882	9.0560	100
88	1	4.088	4.096	5.428	22.211	16.5833	7.4662	100
	2	4.249	4.267	5.448	23.201	17.4018	7.5005	95
	3	4.199	4.164	5.448	22.782	18.3805	8.0679	100
89	1	4.281	4.279	5.657	24.210	25.2798	10.4419	90
	2	4.155	4.162	5.649	23.492	19.0121	8.0929	80
	3	3.989	3.975	5.655	22.520	19.3102	8.5746	80
90	1	4.087	4.106	5.508	22.563	14.0567	6.2299	80
	2	4.234	4.262	5.575	23.685	13.9010	5.8691	60
	3	4.112	4.158	5.516	22.808	13.7275	6.0187	70
91	1	4.178	4.183	5.594	23.389	20.6491	8.8284	80
	2	4.219	4.206	5.687	23.957	17.8289	7.4418	50
	3	4.138	4.171	5.686	23.620	19.5682	8.2845	70
92	1	3.946	3.904	5.530	21.703	20.8493	9.6064	100
	2	4.016	4.032	5.507	22.159	21.8768	9.8725	100
	3	4.194	4.204	5.472	22.977	20.0085	8.7081	100
93	1	4.161	4.154	5.591	23.242	23.1757	9.9714	100
	2	4.041	4.036	5.486	22.157	18.6296	8.4077	100
	3	4.197	4.232	5.606	23.626	21.5610	9.1260	100
94	1	4.300	4.286	5.551	23.832	19.9418	8.3674	100
	2	4.182	4.107	5.559	23.039	17.8066	7.7287	100
	3	4.384	4.351	5.566	24.311	17.7488	7.3005	100
95	1	3.951	3.978	5.606	22.223	19.6660	8.8493	60
	2	3.992	3.985	5.615	22.394	21.5566	9.6260	90
	3	4.211	4.200	5.638	23.709	25.3732	10.7017	90
96	1	4.061	4.020	5.514	22.281	25.5511	11.4676	100
	2	4.166	4.122	5.447	22.573	22.4507	9.9458	100
	3	3.989	3.913	5.446	21.516	21.2229	9.8636	100
97	1	4.026	4.025	5.474	22.033	19.2034	8.7156	100
	2	4.091	4.034	5.550	22.544	21.1117	9.3644	100
	3	4.037	3.999	5.481	22.025	19.0966	8.6701	100
98	1	3.898	3.940	5.612	21.992	20.2221	9.1952	90
	2	4.380	4.373	5.759	25.206	21.6722	8.5980	90
	3	4.150	4.143	5.597	23.208	20.7692	8.9491	100

Table B26. Continued

99	1	3.931	3.952	5.578	21.985	19.7995	9.0059	90
	2	4.180	4.206	5.582	23.403	21.8146	9.3210	90
	3	4.177	4.186	5.563	23.260	20.9649	9.0132	100
100	1	4.412	4.423	5.428	23.979	16.7524	6.9861	90
	2	3.945	3.943	5.466	21.558	17.9356	8.3195	90
	3	4.072	4.110	5.517	22.568	13.9143	6.1655	80
101	1	4.328	4.317	5.612	24.258	23.6295	9.7407	75
	2	4.044	4.028	5.648	22.794	22.6775	9.9486	90
	3	4.061	4.068	5.652	22.971	23.1090	10.0598	50
102	1	4.300	4.303	5.657	24.332	23.0112	9.4571	100
	2	4.056	4.037	5.615	22.722	20.7247	9.1209	100
	3	4.285	4.281	5.566	23.841	20.2265	8.4837	95
103	1	4.252	4.274	5.493	23.414	21.2007	9.0545	100
	2	4.058	4.047	5.491	22.255	20.7692	9.3324	90
	3	4.208	4.192	5.533	23.240	22.7620	9.7943	80
104	1	4.192	4.157	5.544	23.141	19.5504	8.4481	20
	2	4.020	4.021	5.540	22.271	19.4881	8.7504	15
	3	4.347	4.338	5.511	23.931	16.4810	6.8868	15
105	1	4.328	4.323	5.575	24.117	19.9907	8.2891	90
	2	4.256	4.232	5.537	23.498	21.3875	9.1016	100
	3	4.436	4.415	5.640	24.959	21.1607	8.4780	100
106	1	4.141	4.149	5.489	22.753	18.3760	8.0761	100
	2	4.221	4.202	5.489	23.119	19.9196	8.6159	100
	3	4.149	4.205	5.503	22.986	21.4631	9.3374	95
107	1	4.576	4.533	5.450	24.819	23.4782	9.4598	100
	2	4.134	4.084	5.476	22.502	21.6233	9.6092	100
	3	4.256	4.223	5.498	23.307	22.2060	9.5276	95
108	1	4.224	4.229	5.255	22.212	22.4062	10.0874	100
	2	4.186	4.205	5.578	23.402	22.9355	9.8007	100
	3	5.074	5.123	5.634	28.723	27.8999	9.7133	100
109	1	4.088	4.081	5.466	22.325	21.6722	9.7073	100
	2	4.289	4.274	5.577	23.874	25.9248	10.8587	100
	3	4.009	4.008	5.499	22.045	23.3581	10.5957	100
110	1	3.946	3.962	5.479	21.664	22.1571	10.2275	100
	2	3.928	3.901	5.480	21.453	22.9088	10.6784	70
	3	4.279	4.301	5.512	23.646	22.9533	9.7069	80
111	1	4.528	4.487	5.580	25.152	21.2897	8.4642	100
	2	4.402	4.390	5.603	24.632	19.4970	7.9150	100
	3	4.211	4.199	5.611	23.593	18.6251	7.8940	100
112	1	4.058	4.017	5.532	22.335	21.9614	9.8326	100
	2	4.191	4.195	5.550	23.270	23.3403	10.0300	100
	3	4.144	4.101	5.554	22.895	21.1162	9.2230	100

Table B26. Continued

113	1	4.237	4.255	5.474	23.239	13.9188	5.9893	40
	2	4.078	4.087	4.992	20.381	13.8743	6.8074	5
	3	4.108	4.131	5.017	20.667	13.8565	6.7044	30
114	1	4.177	4.155	5.404	22.514	9.6529	4.2875	5
	2	4.155	4.133	5.466	22.651	9.0657	4.0022	20
	3	4.187	4.164	5.544	23.149	9.3192	4.0258	5
115	1	3.975	4.012	5.484	21.900	11.7436	5.3623	50
	2	4.343	4.366	5.429	23.643	12.8556	5.4372	40
	3	4.389	4.333	5.550	24.204	9.7596	4.0321	40
116	1	4.134	4.149	5.517	22.848	9.2614	4.0534	15
	2	4.075	4.074	5.494	22.387	12.6466	5.6490	5
	3	3.790	3.776	5.527	20.907	9.7819	4.6786	10
117	1	4.097	4.054	5.504	22.432	11.0051	4.9059	30
	2	4.361	4.375	5.469	23.888	11.4055	4.7745	5
	3	4.267	4.286	5.498	23.513	8.5408	3.6324	0
118	1	4.303	4.291	5.549	23.843	11.2809	4.7313	5
	2	4.058	4.105	5.466	22.308	11.2987	5.0648	30
	3	4.141	4.204	5.458	22.776	12.9090	5.6678	10
119	1	3.942	3.934	5.584	21.992	6.0809	2.7650	5
	2	4.116	4.107	5.583	22.955	6.4856	2.8253	15
	3	3.978	4.001	5.573	22.230	6.9972	3.1476	20
120	1	3.919	3.923	5.606	21.981	13.2827	6.0427	30
	2	3.932	3.896	5.627	22.026	10.9785	4.9842	0
	3	3.952	3.975	5.613	22.250	13.2515	5.9557	5
121	1	3.910	3.865	5.438	21.141	20.9249	9.8978	50
	2	4.143	4.081	5.500	22.615	22.8110	10.0863	85
	3	4.103	4.103	5.470	22.445	22.9222	10.2125	95
122	1	4.241	4.225	5.490	23.240	23.2647	10.0107	95
	2	4.044	4.034	5.498	22.204	22.1927	9.9949	80
	3	4.072	4.072	5.432	22.116	20.8715	9.4371	90
123	1	4.417	4.403	5.323	23.473	11.3566	4.8381	30
	2	4.450	4.456	5.530	24.625	10.2534	4.1638	0
	3	4.185	4.166	5.561	23.219	10.7293	4.6208	20
124	1	4.045	4.023	5.560	22.430	17.1171	7.6312	45
	2	4.475	4.467	5.503	24.604	16.1874	6.5792	30
	3	4.360	4.342	5.488	23.877	15.8360	6.6322	20
125	1	3.938	3.923	5.448	21.415	9.1413	4.2685	0
	2	4.153	4.140	5.363	22.239	9.3415	4.2005	15
	3	4.128	4.063	5.295	21.682	9.6217	4.4376	20
126	1	3.778	3.788	5.464	20.670	21.8590	10.5749	100
	2	3.997	3.946	5.471	21.728	22.1215	10.1811	100
	3	4.009	3.971	5.475	21.847	21.8590	10.0054	100

Table B26. Continued

127	1	4.016	4.030	5.425	21.825	9.0924	4.1660	20
	2	4.129	4.148	5.513	22.815	10.8984	4.7768	5
	3	4.012	4.045	5.419	21.830	10.2667	4.7029	15
128	1	4.012	4.016	5.602	22.485	11.8904	5.2880	30
	2	4.182	4.181	5.513	23.053	12.4953	5.4202	10
	3	4.216	4.225	5.580	23.554	13.7587	5.8413	20
129	1	4.590	4.590	5.545	25.450	13.4606	5.2891	5
	2	4.263	4.248	5.575	23.727	19.5237	8.2283	15
	3	4.233	4.244	5.563	23.578	16.7390	7.0994	10
130	1	4.224	4.238	5.655	23.928	3.9990	1.6713	0
	2	4.173	4.161	5.613	23.390	6.1031	2.6092	0
	3	4.053	4.037	5.677	22.963	6.8949	3.0026	0
131	1	4.164	4.190	5.545	23.161	11.6857	5.0454	15
	2	4.209	4.214	5.578	23.490	8.9278	3.8006	5
	3	4.258	4.210	5.495	23.268	9.1057	3.9133	10
132	1	4.124	4.107	5.495	22.616	14.0522	6.2134	30
	2	4.150	4.141	5.425	22.493	17.0059	7.5603	40
	3	4.210	4.194	5.420	22.775	13.9366	6.1191	30
133	1	4.140	4.152	5.683	23.562	8.5630	3.6341	0
	2	4.188	4.169	5.584	23.336	11.2720	4.8303	5
	3	4.117	4.119	5.679	23.388	5.7517	2.4592	5
134	1	3.960	3.952	5.450	21.559	18.3226	8.4988	90
	2	4.470	4.450	5.554	24.771	22.9177	9.2517	90
	3	4.721	4.736	5.605	26.499	25.8803	9.7663	100
135	1	4.285	4.285	5.650	24.211	13.2071	5.4549	5
	2	4.054	4.114	5.537	22.612	11.1697	4.9396	40
	3	4.089	4.092	5.685	23.253	12.4686	5.3620	30
136	1	4.500	4.520	5.550	25.029	15.3778	6.1440	60
	2	4.079	4.112	5.556	22.757	20.4712	8.9954	90
	3	4.221	4.225	5.530	23.354	18.8831	8.0856	60
137	1	4.218	4.218	5.546	23.392	17.5175	7.4887	30
	2	4.199	4.224	5.508	23.196	14.1234	6.0887	15
	3	4.195	4.225	5.554	23.381	17.8289	7.6251	70
138	1	3.971	3.933	5.380	21.262	10.9651	5.1571	80
	2	4.185	4.176	5.434	22.717	10.0621	4.4293	65
	3	3.932	3.931	5.429	21.344	8.7054	4.0785	30
139	1	4.081	4.075	5.554	22.648	18.7230	8.2669	90
	2	4.181	4.166	5.495	22.933	18.5895	8.1059	90
	3	4.324	4.296	5.505	23.731	19.6082	8.2627	95
140	1	4.360	4.343	5.505	23.958	18.5895	7.7592	90
	2	3.957	3.970	5.591	22.159	17.5575	7.9233	80
	3	4.473	4.475	5.592	25.019	23.4160	9.3591	90

Appendix C.

Data of

Reinforcing Structural Wood Members

Using the SCRIMP™ Process

Table C1. Shear Strength Dry (MPa) of Standard Dried Laminates

Shear Block	Laminate			
	1	2	3	4
1	12.57198	15.29887	7.39192	8.28479
2		6.11155	25.43630	5.06561
3			11.16199	

Table C2. Shear Strength Wet (MPa) of Standard Dried Laminates

Shear Block	Laminate			
	1	2	3	4
1	9.92231	8.14138	8.92532	6.47560
2	5.89712	7.77527	9.31901	3.46395
3				

Table C3. Wood Failure Dry (%) of Standard Dried Laminates

Shear Block	Laminate			
	1	2	3	4
1	0	100	10	40
2		0	90	5
3			65	

Table C4. Wood Failure Wet (%) of Standard Dried Laminates

Shear Block	Laminate			
	1	2	3	4
1	90	95	100	100
2	80	100	90	25
3				

Table C5. Shear Strength Dry and Wood Failure Dry of IR-Heat Dried Laminates

Laminate	Shear Block	Length 1	Length 2	Width	Area	Load	Shear Strength	Wood Failure
		cm	cm	cm	cm^2	kN	MPa	%
1	1	4.2380	4.2507	5.1295	21.7715	23.2609	10.68410	15
	2	4.2101	4.2367	5.1346	21.6854	14.1891	6.54313	25
	3	3.9611	4.0107	5.1245	20.4255	24.2069	11.85128	10
2	1	4.0894	4.0246	5.1486	20.8879	17.4698	8.36360	90
	2	4.1389	4.1199	5.1410	21.2291	13.7102	6.45821	45
	3	4.2482	4.2723	5.1676	22.0152	14.8449	6.74300	75
3	1	4.0958	4.0589	5.1460	20.9821	27.8169	13.25741	100
	2	4.0894	4.0831	5.0978	20.8307	29.6962	14.25601	20
	3	4.0234	4.0500	5.1270	20.6961	11.6392	5.62388	25

Table C6. Shear Strength Wet and Wood Failure Wet of IR-Heat Dried Laminates

Laminate	Shear Block	Length 1	Length 2	Width	Area	Load	Shear Strength	Wood Failure
		cm	cm	cm	cm^2	kN	MPa	%
1	1	4.1313	4.1377	5.5029	22.7517	13.5752	5.96668	70
	2	4.0894	4.0742	5.6147	22.9178	12.9769	5.66234	75
	3	4.3409	4.3269	5.5690	24.1351	14.4845	6.00142	70
2	1	3.8989	3.9027	5.5004	21.4559	14.0440	6.54555	55
	2	3.9916	3.9853	5.6147	22.3937	7.2755	3.24890	70
	3	4.1859	4.2050	5.5778	23.4015	10.7370	4.58816	100
3	1	4.2405	4.2253	5.4902	23.2396	22.2138	9.55862	100
	2	4.2088	4.2139	5.5778	23.4901	26.3593	11.22147	55
	3	4.0805	4.0754	5.5537	22.6479	15.5231	6.85412	25

BIOGRAPHY OF THE AUTHOR

Leopold Eisenheld was born in Vienna, Austria on June 16, 1970. He was raised in Vienna and graduated from the Technical School in 1989. He attended The University of Agricultural Sciences in Vienna, Austria, and graduated in 1997 with a Graduate Engineer degree in Wood Science. He entered the Forestry graduate program at The University of Maine in the fall of 2000.

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