Manufacture and rehabilitation of guardrail posts using composite fabrics

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Manufacture and Rehabilitation of Guardrail Posts Using Composite Fabrics

Ram Chamarthy

Thesis Submitted to the College of Engineering and Mineral Resources
at West Virginia University
in Partial Fulfillment of the Requirements for the Degree of

Master of Science
in
Mechanical Engineering

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Keywords: Composite Wrapping, Guardrail Posts, Wood, Damping, Dynamic Testing, Hybrid Materials, Composite Materials, Wood-Composite Bond

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ABSTRACT

Manufacture and Rehabilitation of Guardrail Posts Using Composite Fabrics

Ram Chamarthy

The West Virginia Department of Transportation (WVDOT) uses approximately 50,000 wood and 200,000 steel guardrail posts on an annual basis. Steel posts are usually preferred over wood posts since they are easier to install. The relatively large cross-sectional area (39 in²) of wood posts requires expensive equipment for driving them into the ground. The need to develop guardrail posts made of a different material is motivated by the high cost of steel, along with the greater difficulty associated with driving large diameter wood posts.

The primary objective of this study was to develop a Glass Fiber Reinforced Polymer (GFRP) wood post that is more cost effective than a steel post and has smaller diameter than a conventional wood post. Another objective was to develop a portable fabric-wrapping machine for field applications.

Unwrapped and GFRP wrapped posts were tested for flexural properties. The experimental data were compared with published values. Unwrapped and GFRP wrapped posts were tested under dynamic loads to determine their natural frequencies. Free vibration tests of unwrapped, GFRP wrapped, and damaged posts were performed to establish amplitude decay for damping characteristics.

The results obtained for the flexural stiffness (EI) of the posts from static bending tests correlate well with the corresponding results from dynamic testing, both for unwrapped and for GFRP wrapped posts. A two-layer GFRP wrap increases the flexural stiffness of 5.75-inch diameter posts, by 12% according to static tests, or 13% according to dynamic test data. The increase of the log decrement of wood posts due to GFRP wrap is 76%. There was no de-bonding between glass fabric and wood post during exposure to very high temperature (400 °F), up to 4 hours. A portable prototype GFRP wrapping machine is designed and fabricated.
DEDICATION

This report is dedicated to one of the great physicists ever known

Mr. Richard P. Feynman
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I was very fortunate to have Dr. Hota Ganga Rao as my advisor, a person whom I like, admire and respect. I learned a great deal from his approach to the solution of problems and from his philosophical views. His advice and guidance were of great value to me while conducting this research. I also like to express my gratitude to Dr. Ken Means and Dr. Jacky Prucz for their invaluable guidance towards the completion of this research project.

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1. INTRODUCTION

1.1. General Remarks

The West Virginia Department of Transportation (WVDOT) uses approximately 50,000 wood and 200,000 steel guardrail posts on an annual basis. Ease of installation of steel posts compared to wood posts is the primary reason for preference of steel over wood posts. The relatively large cross-sectional area (39 in$^2$) of wood posts over steel requires expensive equipment for driving wood posts into ground. The higher cost of steel posts and greater difficulty associated with driving conventional, larger diameter wood posts are the motivations to find a more practical and economic alternative to wood.

One alternative is to use a smaller diameter wood post with Glass Fiber Reinforced Polymer (GFRP) fabric wrap than conventional wood post. The wrapped wood post is found to be cheaper than a steel post (Anegunta, 2000). Also, the wrapped wood post, compared to conventional wood post, is easier to install because it has smaller diameter. Because of its excellent mechanical properties (i.e., enhanced strength and stiffness over bare wood), GFRP wrapped smaller diameter wood posts can achieve performances similar to a conventional (unwrapped, larger diameter) wood post. The other significant advantages of GFRP wrapped wood posts are: 1) reduction in end-checking and splitting; 2) formation of a moisture-resistant barrier around the post that will minimize decay; 3) enhancement in energy absorption capability. However, one potential disadvantage to GFRP wrapped posts may be damage to the wrap during installation, i.e., driving of post into wood.
1.2. Objective

The primary objective of this study is to develop a Glass Fiber Reinforced Polymer (GFRP) wood post that is cost effective over a steel post and has smaller diameter than a conventional wood post. Another objective of this study is to develop a portable fabric-wrapping machine for field applications.

1.3. Scope

To achieve the objective of developing a GFRP wrapped guardrail posts, a research program that has both fundamental and applied aspects was proposed. The scope of this research was divided into the following tasks:

- Static Testing: Unwrapped and GFRP wrapped posts are tested for flexural properties in bending test. The experimental data are verified with theoretical values.

- Dynamic Testing: Unwrapped and GFRP wrapped posts are tested under dynamic loads to determine their natural frequencies. The modulus of elasticity obtained using the frequency equation (Blevins, 1979) is verified with static test data.

- Damping Testing: Under free vibration mode, unwrapped, GFRP wrapped, and damaged posts are tested and evaluated for dynamic amplitude decay and log (logarithmic) decrement.

- Wrapping Machine: A prototype portable GFRP wrapping machine rotating about the vertical axis is designed and fabricated for field applications.
1.4. Report Organization

- Review of available literature has been carried out and reported in Chapter 2, with a general description on wood, fabrics and resins and emphasis on composite materials and test methods of GFRP wrapped wood members.

- Chapter 3 deals with test specimen preparation (GFRP wrapping of posts). In addition, the machines used to wrap the posts are discussed.

- Test setup and methodology of testing (static, dynamic, damping) are presented in Chapter 4.

- The experimental data obtained from static and dynamic test methods are presented in Chapter 5.

- Chapter 6 provides an analysis and discussion of experimental data of all the tests conducted during this study.

- Finally, Chapter 7 presents the conclusions and recommendations for future research on GFRP wrapped posts.

Detailed technical information supporting the data evaluation and conclusions is given in the following appendices:

- Screen captures from dynamic test are presented in Appendix A.
- Charts of dynamic test are presented in Appendix B.
- Charts of static test are presented in Appendix C.
- Screen captures of damping test are presented in Appendix D.
- Charts of damping test are presented in Appendix E.
• Pictures of parts used to fabricate Vertical Axis Wrapper are presented in Appendix F.
• Scanned picture of data published on log decrement of wood are in appendix G.
2. LITERATURE REVIEW

2.1. Introduction

Many studies have been conducted on performance GFRP wrapped wood members. The studies presented here in relate to tests on shear, compression, tensile strength, confinement, strain and bending. In the following sections, studies relevant to different resin combinations, micro- and macro-level tests (bending, shear and fatigue), non-destructive tests and effect of aging media are discussed, with emphasis on accelerated aging techniques.

2.2. Accelerated Aging Technique

Quality and failure of wood crossties have been judged based on actual performance. The service life of treated wood crossties in the United States is typically 20-30 years; thereby it takes at least 20-30 years to obtain the results from field. Chow (et. al.,1987) conducted a test to develop suitable short-term test methods and to establish correlations between short-term test results and long-term in-service performance of wood cross ties. Chow’s results have shown that the six-cycle accelerated aging process could be equivalent to more than 20 years of natural aging. Each accelerated aging cycle consisted of vacuum soaking, pressure soaking, freezing and oven drying. The six-cycle aging process and natural weathering significantly affect the hardness and compression properties perpendicular to grain.

2.3. Adhesive for Wood-GFRP Interface

Adhesives that are excellent for bonding certain wood species may not be as well suited for other materials. As an example, phenolics have
been the mainstay in production of exterior-type softwood plywood, but their high-temperature curing requirements keep them from being practical for laminated timbers. Such timbers would explode from steam formation in the interior if heated to a temperature that is required to cure phenolic-type adhesives (Selbo, 1975). Rowlands, et. al., (1986) used ten adhesives (three epoxy resins, two resorcinol formaldehydes, two phenol resorcinol formaldehydes, two isocyanates, and one phenolformaldehyde) to bond numerous reinforcements (uni- and cross- woven glass, Kevlar, and graphite fibers). Rowlands, et. al., evaluated shear stress and tensile strength as per ASTM (American Society for Testing and Materials) D 905 and ASTM 1344-72, respectively. To evaluate durability of various glass-adhesive systems, ASTM D 2559 was used as the accelerated aging standard for specimens. The results have shown that the epoxies (e.g., manufactured by Dow and Ciba) exhibited good performance with glass, aramid and graphite fibers. Neither isocyanates nor the phenolformaldehyde performed well in the test (Rowlands, et. al., 1986).

Kshirsagar (1998) conducted tests to investigation of the durability of composite materials employed for rehabilitation of concrete bridge piers. Standard concrete cylinders (4- x 8- inch dimensions) wrapped with 1 layer of glass fabric embedded in an epoxy resin matrix were used to simulate the field situation. Wet lay-up method was used to wrap the concrete cylinders where the epoxy also served the purpose of bonding the composite to the concrete. Specimens were subjected to six different accelerated aging conditions: (i) pH 9.4, 73 °F (ii) pH 12.4, 73 °F (iii) pH 12.4, 150 °F (iv) pH 7.0, 150 °F (v) Dry Heat at 150 °F and (vi) Extended Freeze-thaw Cycles with 100% RH. Specimens were then tested for changes in ultimate strength and ultimate strain when exposed to 1000, 3000 and 8000 hrs of aging. Concrete cylinders wrapped with 2 and 3 layers of fabric were also tested to failure under compression. A higher jacket thickness on the load resisting capacity of the cylinder was tested to evaluate the confining effect. Coupon level tests consisted of Dynamic
Mechanical Thermal Analysis (DMTA), and tension tests conducted on separate composite coupons that were aged in a similar environment as the cylinders. DMTA tests revealed some changes in the polymer glass transition temperature and in the modulus of the composite, while tension tests showed changes in the strength and the ultimate strain to failure. These results were used to understand and explain the causes of failure of the aged wrapped cylinders. Accelerated aging of the wrapped cylinders resulted in a considerable reduction in the ultimate strength and strain when exposed to moisture at 150 °F. This change was independent of the pH of the liquid medium employed. Cylinders exposed to extended freeze-thaw cycles also experienced similar reduction in strength and ductility after 3000 hrs of aging. Significant reduction in both the tensile strength and the strain-to-failure of the FRP coupons aged in pH 12.4 solution at 150 °F for 1500 hrs suggested that the composite became brittle upon aging. DMTA tests indicated a split in tan δ curve for the coupons exposed to moisture. A bi-linear stress-strain model was developed that attempted to predict the ultimate strength and ultimate strain in the wrapped cylinder failed under compression. The bi-linear model was further extended to incorporate changes in the properties of the composite after aging. The damage model thus obtained, attempted to estimate the residual strength and ductility of the wrapped cylinders after aging based on the results obtained from tension tests. Good agreement was obtained between the values predicted by the model and the experimental results. It was concluded that the composite wrap is useful to enhance the strength and ductility of the concrete cylinder. These properties were retained throughout the aging period when exposed to dry heat or moisture at ambient temperature suggesting an appreciable durability of the composite material.

Anegunta (2000) wrapped CCA (Chromated Copper Arsenate) treated southern pine dowels of diameter 0.5-inch with E- glass fabric (0-45 degree). The length of samples was 7.5-inch. HMR (Hydroxy
Methylated Resorcinol) was used as a primer, and epoxy (TYFO-S) was used as an adhesive. Samples were subjected to five different conditions (6 cycle accelerated aging, freeze thaw cycles in acidic solution, alkaline solution and in 3% salt water). Three point bending tests were used to evaluate flexural rigidity of test samples in different conditions. The results have shown that composite wrapping of wood with HMR/epoxy/glass fibers increases the flexural rigidity of wood by 2.62 times under unaged conditions and by 1.77 times under six cycle aging. The wrapped samples were damaged the most by freeze-thaw cycling in acidic solution.

Chang (1993) studied stress laminated decks made of northern red oak. The objective was to study fatigue life and fatigue behavior of stress-laminated decks under different conditions such as prestress level, butt joint arrangement, and maximum applied cyclic stress. The energy analysis was used to evaluate stress-laminated beams under mechanical fatigue loading.

Talakanti (1997) wrapped quarter-scale specimens (2.5-inch x 2.5-inch x 36-inch) using filament winding process. A total of six wrapped and non-wrapped wood crossties of 30-inch length were tested. The load was applied at the midspan of simply supported specimen in upward and downward direction. The test was designed to apply stress reversals on the specimens. The results of this test have shown that wrapped specimens have lower rate of stiffness degradation compared to non-wrapped specimen. Both the wrapped and non-wrapped specimens have shown gradual reduction in stiffness when subjected to mechanical fatigue loading. Fatigue tests of GFRP wood ties using filament winding (2.5-inch x 2.5-inch x 36-inch) were conducted by Talakanti (1997). The fatigue tests were similar to a three point bending test except that the load moved in upward and downward direction (tension-compression) at midspan resulting in compressive and tensile strain of around ±3250x10^-6 in/in on the surface of samples for 2.7 million cycles. The static tests were conducted at every 100,000 cycles. Strain on wood and wrap surfaces
were measured. If there is 100% compositeness between wood and wrap, the strain on wood and wrap surfaces are expected to vary linearly when samples are subjected to static testing. The results show that the strain on wrap surface was slightly higher than strain on wood due to the fact that the wrap surface was farther from neutral axis than the wood surface. One hundred percent compositeness between wood and wrap was found up to 2.5 millions. After 2.5 million cycles, the strain on wood surface became non-linear while the strain on wrap surface remained linear. This shows that the beam samples lost their compositeness between wood and wrap. This loss of compositeness or degradation occurred after 85% of mechanical fatigue life. Therefore, it is concluded that the GFRP-wood adhesive interface was intact during 85% of the fatigue life at strain range of ±3250x10⁻⁶ in/in.

Laosiriphong (2000) conducted bending and fatigue tests on unwrapped and wrapped crossties to select compatible adhesive between creosote treated wood and glass fabric, and study the performance of wrapped wooden crossties. Five primer/resin combinations (Resorcinol Formaldehyde group) were screened for strength and durability of treated wood crossties. To evaluate stiffness and durability of wrapped samples under natural environmental conditions (simulated by six cycles aging), half scale wooden crossties (3-inch x 4-inch x 42-inch) were wrapped with glass fabric at midspan over a length of 20-inch before subjecting them to three point bending test. These tests were conducted on half-scale samples, before and after accelerated aging conditions. To study the performance of GFRP full-scale crossties, fatigue testing was carried out on full-scale unwrapped and GFRP wrapped specimens. Full-scale crossties were wrapped over the rail-seat zones and then embedded in ballast under flexural fatigue. The experimental deflections and bending moment correlated well with the analytical values using the bending theory of beams on elastic foundation. The following describes the conclusions of Laosiriphong’s work.
• The primer/resin combination of G1149A/G1131A + G1131B is recommended for wrapping crossties because they have high bond strength and high percentage of wood failure for creosote treated wooden crossties compared to other primer/resin combinations.

• The primer/resin combination of G1260/Epoxy did not survive the stresses induced under accelerated aging process.

• During wrapping of crossties, tension should be applied uniformly to glass fabric (wrap materials) to ensure good bond between the wrap and the crossties.

• Glass fiber should be saturated thoroughly with low viscosity resin while crossties are wrapped.

• For half-scale crossties, glass fiber reinforcement enhanced flexural rigidity by 44 percent and shear modulus by 18 percent.

• In the half-scale wrapped crossties, no significant change is noted in flexural rigidity before and after applying accelerated aging technique.

• The wrapped crossties were able to withstand fatigue to 2 million fatigue cycles without any damage.

• In full-scale wrapped crossties, there was no de-bonding between glass fabric and crosstie up to 600,000 fatigue cycles.

• There is a good correlation in deflection and bending moment of crossties between the experimental and theoretical results (using finite beam theory on elastic foundation).

• The lateral movement and gage change of crossties were not affected in the field over a period of 6 months.

• The moisture content of test samples taken from the wrapped area was about 2% to 9% more than that of samples taken from the non-wrapped area; because moisture cannot evaporate in the wrapped area as quickly as in the non-wrapped area.
• Spike pulling force for a wrapped crosstie was about 30%~70% more than the unwrapped crossties. This might be attributed to the enhancement in strength in the wrapped crossties.

2.4. Nondestructive Dynamic Testing

Aluri (2000) conducted a study to engineer a non-contact laser vibration sensing system for evaluation of mechanical properties, damage detection and remaining life assessment. Four different damage scenarios for the AVLB were simulated and testing was done for all four damage states, as well as in the undamaged state. Modal frequencies for each damage state of the AVLB were identified by testing the structure under swept-sine excitation. Resonant sine-dwell testing was conducted on the AVLB and the first three bending mode shapes were obtained. FE analysis was conducted on the AVLB model to validate the experimental results. The modal strain energy based algorithm was used on AVLB because of its higher sensitivity in identifying the damage location and magnitude than frequency shifts and change in mode shapes. Damage location was successfully identified in two of the four simulated damage states. The following items illustrate the accomplishments of this effort: A prototype automated laser-based sensor system was designed and built, to test the AVLB. The system includes a laser vibrometer, automated robotic gantry, data acquisition system and a control program. Modal testing was done on the AVLB using the automated sensor system to study the modal characteristics of the AVLB and establish the validity/accuracy of the automated system. The modal parameters such as natural frequencies and mode shapes show a good correlation between experiment and FE (model supplied by the U.S. Army). Four damage scenarios were simulated and the AVLB and mode parameters were obtained for all the four damage states and in the undamaged state. The strain energy based damage detection algorithm was applied to the AVLB test data and damage was clearly located in 2 out of the 4 damage cases.
The natural frequencies obtained from dynamic testing using the non-contact laser vibration sensing system (Laser-Vibrometer) are used to obtain the mechanical properties (stiffness, strength and flexural modulus) and damping properties of GFRP wrapped wood posts.

### 2.5. Materials

Fiber Reinforced Polymer (FRP) composites are composed of fibers (such as glass or carbon) wet and cured in a polymer matrix. FRP composite materials are typically characterized by excellent tensile strength in the direction of the fibers. Glass FRP composites are also characterized by relatively low modulus of elasticity in tension and are corrosive resistant. In this study, a hybrid member is defined as a wood post wrapped with GFRP (phenolic resin-saturated glass fabric). Properties of constituent materials of composites, such as fiber sizing, resin type, fillers, and accelerators influence the mechanical properties as well as the behavior of hybrid materials (viz., fiber-reinforced wood post). Typically, a fiber-reinforced composite consists of 50 to 70% of fibers by weight embedded in polymer matrix. In this chapter, characteristics of wood is described first, followed by different types of fabrics and polymers, along with their mechanical properties before embarking on extensive testing and evaluation of hybrid (wood and FRP) posts.

#### 2.5.1. Wood

The chemical composition, structure and treatment of wood are emphasized herein because of their influence on static and dynamic response variations from one species to another, and also their influence on glassfabric reinforced wood members.
2.5.1.1. Natural Characteristics

Wood is a naturally orthotropic material with elastic properties differing in each of the three perpendicular planes (Figure 2-1). The following describes the different components of a section of a tree.

![Figure 2-1 Cross-Section of Wood](image)

As shown in Figure 2-1, bark consists of two parts, the outer (corky, dead) part, A, and the inner (thin, live) part, B. Wood, which in most species may be differentiated between sapwood, D, and heartwood, E. The pitch, F, a small central core darker in color, where primary growth originates. The cambium layer, C, where all growth in thickness of bark and wood arises by cell division (Gurfinkel, 1973).
2.5.1.2. Chemical Composition

Wood consists of organic matter such as carbon, hydrogen, oxygen, and a small amount of nitrogen. A typical wood substance, irrespective of species, contains typically 50% carbon, 6% hydrogen and 44% oxygen together with 0.1% of nitrogen. In addition to organic matter, wood contains a number of mineral substances in small amounts. These fundamental elements are combined with each other in wood to form complex chemical substances such as cellulose and lignin, which form the cell walls. Of the two, cellulose is the most abundant constituent, comprising about 70 % and lignin ranging from 18 % to 20 % of wood. Lignin cements the structural units of wood fibers together and so it is responsible for the characteristics rigidity and hardness of wood. It also helps to reduce water absorption, thereby increasing the dimensional stability of wood. In addition to cellulose and lignin, the wood structure contains a small amount (0.2% to 1.0%) of minerals, which are formed if wood is burned (i.e., where lignin and cellulose are burned). These minerals are the plant-food elements of the tree. Also enclosed in the cavities of the cells are various extractives that contribute to wood color, odor, taste and resistance to decay. These extractives, which can be extracted from the wood by neutral solvents such as water and alcohol, include tannins, starch, coloring matters, oils, resins, fats, and waxes.

Wood is a cellular organic material whose porosity and surface condition affect its characteristics as a substrate. The bondability of the wood/adhesive system depends on many factors: species, equilibrium moisture content, physiochemical properties of wood (including the changes caused by preservative treatment or exterior exposure), adhesive properties, and the conditions under which the adhesive bond is formed. Northern oak, eastern cotton wood, southern pine, red maple, yellow-poplar and douglas-fir are the most commonly used types of wood for structures.
2.5.1.3. Structure

Wood is composed of cellulose, hemicellulose and lignin. The arrangement of these components is similar to that of a fiber reinforced composite wherein, the anisotropic cellulose fibers are reinforced in isotropic lignin matrix. The partially oriented hemicelluloses are intimately connected to the other two components. The amount, organization and structure of these components influence the adhesive bonding of wood. A high cellulose content in wood leads to an increased tensile strength and high lignin content improves compressive strength parallel to the grain.

2.5.1.4. Treatment

Natural or artificial weathering can produce significant changes in wettability and bondability of wood. Wood used in building construction is generally subjected to fluctuating humidity. The EMC (Equilibrium Moisture Content) is therefore constantly changing, sometimes periodically and at other times, sporadically, such as when wood is exposed to rain. Hence wood is treated with chemicals to enhance performance against fire, fungi and weather.

Chromated copper arsenate, copper naphthenate, creosote, ammoniacal preservative solutions like ammoniacal copper zinc arsenate (ACZA) and ammoniacal copper arsenate (ACA), chromated zinc chloride etc. are some of the preservatives used for the treatment of wood.

Creosotes distilled from tars are widely used in wood preservation, and coal-tar creosote is most effective among the creosotes. High toxicity to wood destroying organisms, relative insolubility in water, low cost and ease of application to wood are the advantages of this preservative. However, the blackish-brown color renders it unsuitable where appearance is important. Also, creosote vapors are harmful to plants. Freshly creosote-treated wood can be ignited easily and so creosote cannot be used where fire hazard is a concern.
Water based chromated copper arsenate (CCA) is the most widely used preservative. Experiments conducted at the Wood Research Institute, Michigan Technological University, indicated that wood (southern yellow pine, radiata pine and douglas-fir) thoroughly impregnated with CCA even at low retentions could be protected from damage by formosan subterranean termites, the common termites affecting wood in North America. Also, CCA treated wood is found to provide good resistance to Limnoria and Teredo marine borer attack. CCA is accepted as a very effective preservative treatment with certain wood species like pine wood and douglas-fir. Commercial CCA treatments are also known to contain wax emulsions that greatly increase the water-repellancy of the treated wood as compared to untreated wood. This is due to the higher contact angle for the CCA treated wood (Anegunta, 2000).

2.5.2. Fibers

Fibers are produced in many different forms to suit specific industrial or commercial applications. Certain technical issues on fibers and fabrics are highlighted herein because the mechanical properties of composite materials are influenced by the type of fiber/fabric used. Fibers can be made of different materials such as glass, carbon, aramid (Kevlar), boron, etc. Fibers may be continuous or discontinuous and classified as: 1) Unidirectional fibers; 2) Chopped strand fiber mats; 3) Woven, stitched, or braided fabrics; 4) Bi-directional fabrics; and 5) Whiskers (short fibers). The most commonly used fibers are the unidirectional fibers, which are single layers of yarn. These are the strongest type of fibers in tension. Fiber strength is maximum along the fiber direction whereas they are weak in the perpendicular direction.

Fabrics are formed from fibers or yarns with or without interlacing. They are produced to meet the strength requirements in different directions unlike the unidirectional fibers. Also, fabrics keep fibers aligned prior to resin impregnation, especially in case of a complex part processed.
through pultrusion or resin transfer molding technique. Fabrics are the principal constituent of the fiber-reinforced composite materials. They resist over 90% of the load acting on a composite structure. Hence, using a combination of fabrics is important when designing a composite part that has to resist complex stress state. The properties of a composite laminate, such as compressive strength, compressive modulus, tensile strength, tensile modulus, flexural strength, flexural modulus, fatigue strength, thermal conductivity and cost are influenced by: 1) type of fabric; 2) weight of fibers in fabric; and 3) Orientation of the fibers in the fabric. The most commonly used fabrics in composites are glass, carbon and aramid fabrics. In the following sub-sections, properties of different types of fibers are discussed (Hota, 2003).

2.5.2.1. Glass Fibers

Glass fibers are the most commonly used fibers for many engineering applications because of its cost and strength properties. Glass fibers are made from molten glass spun from an electrically heated platinum-rhodium alloy bushings (or furnace) at a speed of 200 mph. These filaments cool from a temperature of 2192 °F to room temperature within 10⁻⁵ seconds. Glass fibers have a diameter ranging from 0.00009- to 0.00035-inch (i.e., 90 microns to 350 microns). A protective coat called size is applied to individual filaments before they are gathered together into a strand and wound on a drum. A strand is a basic form of commercially used continuous glass fibers and consists of two hundred and four (204) parallel filaments. Strands are combined to form thicker bundles than roving (CISPI, 1992). Sizing (protective coating) is a mixture of lubricant, antistatic agent, and a binder that performs the following functions: 1) Reduces the abrasive effect of filaments rubbing against one another; 2) Reduces static friction between the filaments; 3) Packs filaments together into a strand; 4) Reduces the damage to fibers during mechanical handling; and 5) Facilitates the molding process.
Several types of commercially available glass fibers identified are: E-glass, Z-glass, A-glass, C-glass, R- or S-glass, K-glass, D-glass (dielectric glass). The two commonly used types of glass fibers in GFRP industry are E-glass (electric grade) and S-glass (high strength). Chemical composition of E- and S-glass fibers are presented in Table 2-1 (Gibson, 1994).

<table>
<thead>
<tr>
<th>Type of fibers</th>
<th>Ingredients (weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO₂</td>
</tr>
<tr>
<td>E-glass</td>
<td>54.5</td>
</tr>
<tr>
<td>S-glass</td>
<td>64</td>
</tr>
</tbody>
</table>

Chemical structure of E- and S-glass fibers indicates silica (SiO₂) as the principal ingredient. Oxides such as Boric Oxide (B₂O₃) and Aluminum Oxide (Al₂O₃) are added to modify the network structure of SiO₂ and to improve workability. The Na₂O and K₂O content are low to give E- and S-glass fibers a better corrosive resistance against water as well as higher surface resistivity.

The E-glass fibers have the lowest cost of all commercially available reinforcing fibers and therefore it is most widely used in composite applications. Their advantages are:

- Low cost
- High tensile strength
- High chemical resistance
- Relatively high fatigue resistance
- Excellent insulation properties
The limitations of E-glass fibers are:

- Low tensile modulus
- Relatively high specific gravity
- Sensitivity to abrasion with handling
- High hardness

2.5.2.2. Carbon/Graphite Fibers

Carbon fibers are the strongest, stiffest, and most durable of all types of fibers. They are described as fibers consisting at least 90% carbon obtained by the controlled pyrolysis of appropriate fibers. If the amount of carbon exceeds 99%, then the fibers are called graphite fibers. A large variety of precursors are used to manufacture different types of carbon. The most commonly used precursors are polyacrylonitrile (PAN), petroleum or coal tar pitch, cellulose fibers (viscose rayon, cotton), and certain phenolic fibers. The properties of carbon fibers are influenced by the processing conditions, such as tension and temperature during manufacturing process. Carbon fibers do not have stress corrosion or stress rupture at room temperatures. In addition, they can be used in applications requiring high temperature resistance, chemical inertness and damping characteristics. On the basis of precursor materials, fiber properties, and final heat treatment, carbon fibers can be classified into the following categories discussed below.

2.5.2.2.1. Based on Precursor Materials

- PAN-based carbon fibers
- Pitch-based carbon fibers
- Mesophase pitch-based carbon fibers
- Isotropic pitch-based carbon fibers
- Rayon based carbon fibers
- Gas-phase-grown carbon fibers
2.5.2.2.2. Based on Fiber Properties

- Ultra-high-modulus (UHM) with modulus greater than 450 GPa
- High-modulus (HM) with modulus between 325-450 GPa
- Intermediate-modulus (IM) with modulus between 200-325 GPa
- Low-modulus and high-tensile (HT) with modulus less than 100 Gpa and strength greater than 3 GPa
- Super high-tensile (SHT) with tensile strength greater than 4.5 GPa

2.5.2.2.3. Based on Final Heat Treatment Temperature

- Type 1 (high-heat-treatment carbon fibers): associated with high-modulus type fibers and temperatures greater than 3000 °C
- Type 2 (intermediate-heat-treatment): associated with high-strength type fiber and temperature between 1500 °C and 2000 °C
- Type 3 (low-heat-treatment carbon fibers): associated with low modulus and low strength fibers and temperature less than 1000 °C

Carbon fibers are manufactured from synthetic fibers through heating and stretching treatments. PAN and pitch are the two most common precursors (raw materials) used for manufacturing carbon fibers. PAN is a synthetic fiber, which is pre-manufactured and wound onto spools, whereas pitch is a coal-tar petroleum product, which is melted, spun, and stretched into fibers. The fibers are subjected to different treatment schemes, viz., thermosetting, carbonizing, and graphitization. Carbon fibers offer the following advantages:

- High tensile strength-to-weight ratio
- High tensile modulus-to-weight ratio
- Very low coefficient of linear thermal expansion and even negative coefficient of expansion (contraction) under increased temperatures
- High fatigue strength
Some of the disadvantages of carbon fibers are:

- High cost
- Fibers are brittle which may reduce the impact resistance
- Fibers have electrical conductivity, which limits their application potential

2.5.2.2.4. PAN vs. PITCH Carbon Fibers

PAN carbon fibers are produced using higher-cost polymers, whereas PITCH carbon fibers are made using lower-cost feedstock from petroleum or coal tar. Pan carbon fibers are primarily used as structural reinforcements because of their high tensile strength. PITCH carbon fibers, with lower tensile strength, are customized to meet specific application needs.

The arrangement of carbon atoms in multiple planes, the forces between these planes and the bonds between the atoms in a plane, result in highly anisotropic physical and mechanical properties of the carbon fibers. The major differences in mechanical properties of glass and carbon are shown in Table 2-2 (Gibson, 1994).
Table 2-2 Mechanical Properties of Glass and Carbon Fibers

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength E+03 psi</th>
<th>Tensile modulus E+06 psi</th>
<th>Density lb/in³</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass fibers</td>
<td>500.0</td>
<td>10.5</td>
<td>0.092</td>
</tr>
<tr>
<td>S-glass fibers</td>
<td>650.0</td>
<td>12.5</td>
<td>0.090</td>
</tr>
<tr>
<td>Carbon fibers (PAN based precursor)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS-4</td>
<td>580.0</td>
<td>33.0</td>
<td>0.065</td>
</tr>
<tr>
<td>IM-7</td>
<td>785.0</td>
<td>40.0</td>
<td>0.064</td>
</tr>
<tr>
<td>T-300</td>
<td>530.0</td>
<td>33.5</td>
<td>0.064</td>
</tr>
<tr>
<td>T-650/42</td>
<td>730.0</td>
<td>42.0</td>
<td>0.064</td>
</tr>
<tr>
<td>Carbon fibers (Pitch based precursor)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-55</td>
<td>250.0</td>
<td>55.0</td>
<td>0.072</td>
</tr>
<tr>
<td>P-75</td>
<td>300.0</td>
<td>75.0</td>
<td>0.072</td>
</tr>
<tr>
<td>P-100</td>
<td>325.0</td>
<td>100.0</td>
<td>0.078</td>
</tr>
</tbody>
</table>

2.5.2.3. Aramid Fibers

DuPont Company commercially produced Aramid fibers under the trade mark of Kevlar. The chemical composition of Kevlar is poly-para-phenylene diamine-terephalamide (PPD-T). The repeat unit in Kevlar fiber molecules contains an amide \(\text{−}_N\text{−}_N\) group and an aromatic ring. It is made from a condensation reaction of para-phenylene diamine and terephthaloyl chloride. The resultant aromatic polyamide contains aromatic and amide groups. Polymers with high breaking strength often have one
or both of these groups. The aromatic ring structure contributes high thermal stability. The para configuration leads to stiff, rigid molecules that contribute high strength and high modulus.

Tensile modulus is a function of molecular orientation. As a spun fiber, Kevlar 29 (a high toughness variant) has a modulus of 62 Gpa. Heat treatment under tension increases crystalline orientation. The resulting fiber, Kevlar 49, has a modulus of 131 Gpa.

The tensile strength of Kevlar ranges from about 2.6 to 4.1 Gpa. Tensile failure initiates at the fibril ends and propagates via shear failure between the fibrils.

Advantages:

- Very low thermal conductivity
- Very high damping coefficient
- High degree of yielding under compression, i.e., high toughness

Disadvantages:

- Aramid fibers are hygroscopic
- Low compressive strength
- Modulus loss at elevated temperatures
- Difficult to cut and machine
- Sensitive to ultraviolet lights (UV), i.e., property deterioration with time

2.5.2.4. Boron Fibers

Boron fibers are produced by a chemical vapor deposition (CVD) from the reduction of boron trichloride ($\text{BCl}_3$) with hydrogen on fine tungsten wire or carbon monofilament substrate (Agarwal and Broutman, 1990). Boron fibers have very high tensile modulus in the range of 50 - 60 x 10^6 psi. Some advantages of boron fibers are high tensile modulus and good resistance under compressive loads to buckling.
2.5.3. Polymers

Polymers are organic compounds formed by carbon. Certain technical issues on polymers are highlighted herein because the mechanical properties of composite materials are influenced by the type of polymer used. They can be obtained either from nature or through synthesis of organic molecules in the laboratory. A polymer can be defined as a long-chain molecule having one or more repeating (poly) units (mers) of molecules joined together by strong covalent bonds. These repeating units (subunit) are called monomers. Two subunits bonded together to form a dimer, and bonding of three subunits leads to a trimer, and bonding of many subunits leads to a polymer. A plastic or polymeric material is a collection of large number of polymer molecules of similar chemical structure, but not necessarily equal length (Gerig, 1974). The term polymerization refers to a chemical reaction or curing, which leads to a composite in the presence of fibers. The transition period from a liquid state (monomer) to a solid (matrix) state is generally referred to as the cure time; it is a function of temperature during cure. Polymers may be in solid or liquid state and cured polymer is referred to as matrix. Matrices themselves do not contribute any significant strength (except interlaminar or in-plane force transfer) to a composite since most of the load is taken by the fibers. When a load is applied to a composite, the matrix helps in transferring the loads between the fibers. The matrix also protects the fibers partially against environmental attack and their surface from mechanical abrasion. Polymeric materials, referred to as matrices after cure, are commonly available in two types: thermosets and thermoplastics. Thermoplastics are available in granular form whereas thermosets in liquid form. Choosing the type of polymer to form a matrix material is important because of its important role on the in-plane shear properties and interlaminar shear properties, i.e., between laminae of a laminate. For example, interlaminar shear strength (in-plane shear transfer
from one laminae to the other) is important in structures under bending, whereas the in-plane shear strength is important for structures under torsion requiring resistance to in-plane shear. The matrix also provides lateral support for fibers against buckling under compression or a combination of forces. A significant difference between thermoset and thermoplastic polymer is the behavior under heat and pressure. Different types of polymers are presented below (Hota, 2003).

2.5.3.1. Thermoplastic Polymers

Thermoplastic polymers are organic compounds that occur in granular form. They consist of linear molecules that are interconnected by secondary weak bonds (intermolecular forces) such as van der Walls bonds and hydrogen bonds (Mallick, 1993). These polymers will melt upon heating and take the form of resin. This enables the resin to be reshaped when heated. The mechanical properties of thermoplastics degrade with repeated heating and cooling cycles. Thermoplastics provide better impact resistance and toughness and absorb higher levels of moisture than thermosets. The processing time of thermoplastic resins is quicker than thermosets, and lead to extended fabrication options such as injection molding due to lower viscosity. Some of the most commonly available thermoplastic polymers are:

- Acrylonitrite butadiene styrene (ABS)
- Acetal
- Acrylics
- Fluropolymers
- Polyvinyl chloride (PVC)
- Polycarbonate
- Polyethylene
- Polypropylene
- Polysulfone
• Polyether ether ketone (PEEK)

2.5.3.2. Thermoset Polymers

Thermoset polymers are often referred to as thermoset resins. Thermoset resins have molecules that are joined together by cross-links between the linear molecules forming a three-dimensional network structure. Once cross-links are formed during curing, the resin cannot be melted and reshaped through heat and pressure. They are formed of low molecular weight liquid chemicals with very low viscosities. The reasons for using thermoset resins in composites are:

• Better bonding between the fibers and the matrix
• Ability to cure at room temperature
• Excellent creep resistance

Cure of thermoset resins at room temperature or elevated temperature leads to cross-linking. Cross-linking releases heat as the resin cures (exothermic). Cure rate can be controlled in terms of shelf life and gel time through proper proportioning with a catalyst. Special resin formulations can be developed to improve impact and abrasion resistance. Some of the commercially available resins are discussed below:

2.5.3.2.1. Polyesters

Unsaturated polyesters are the most widely used resins on account of their relative low costs. They represent 75% of the total thermoset resins that are being used by the composite industry. The polyesters are produced by the condensation polymerization of dicarboxylic acids and dihydric alcohols (glycols). A reactive monomer, such as styrene is used for the finished polymer to obtain low viscosity. Polyester resins are cured with conventional organic peroxides and the cure is exothermic, i.e., cross-linking process releases heat as it bonds. Usually polyesters are supplied with fast cure time. Although the strength and modulus of
polyester resins are lower than those of epoxy resins, they have a variety of properties that range from hard and brittle to soft and flexible. The major disadvantage of polyester resins is its high volumetric shrinkage (5% - 12%), which can leave sink marks (uneven depression) in the finished product. This defect can be reduced by partly combining a low-shrinkage polyester resin that contains a thermoplastic polymer (Cossis and Talbot, 1998). Some of the common commercial types of unsaturated polyester resins are:

- Orthophthalic Polyester (OP)
- Isophthalic Resin (Isopolyeste)
- Bisphenol A Furmerates (BPA)
- Chloroendics

2.5.3.2.2. Vinylesters

Vinylesters are unsaturated resins. They are produced by reacting epoxy resin with acrylic or methacrylic acid (unsaturated carboxylic group), which produces an unsaturated stage, and thus makes them very reactive. The resulting material is dissolved in styrene to give a product that is very similar to a polyester resin. Vinylester resins are cured with the same conventional organic peroxides as conventional polyesters. They offer excellent corrosion resistance. They have higher fracture toughness than epoxies. Excellent mechanical properties combined with toughness and resilience of vinylester is due to their molecular weight and the epoxy resin backbone. Vinylesters, when combined with acid resistant epoxy backbone, give excellent resistance to acid and caustics. Vinylester resins have a low viscosity and fast curing time like polyester resins. A disadvantage of vinylester resins is their high volume shrinkage (5% - 10%). They have moderate adhesive strength when compared to epoxy resins.
2.5.3.2.3. Epoxies

Epoxies are characterized by the presence of one or more three-membered rings. These rings are variously known as the epoxy, epoxide, or ethoxyline group, and an aliphatic, cycloaliphatic or aromatic backbone (Dewprashad and Eisenbraun, 1994). The starting materials for epoxy materials are low-molecular-weight organic liquid resins containing a number of epoxide groups, containing one oxygen and two carbon atoms (Penn and Wang, 1998). Other organic molecules are added to the epoxide group to formulate a thermoset resin, which undergoes curing to form a matrix.

Since epoxy resins are mutually soluble, blends of solids and liquids or with other epoxy resins can be used to achieve specific performance features or specific properties. The most widely used epoxy resin is diglycidyl ether of bisphenol A and higher-molecular-weight species. Epoxies are cured by adding an anhydride or an amine hardner. The cure rates can be controlled through proper selection of hardness and/or catalyst process requirements. Epoxies are used in high-performance composites to achieve superior mechanical properties and resistance to corrosive environment. Epoxies are more expensive than other resins and have a much higher viscosity than most polyester resins, which makes epoxies more difficult to use (CISPI, 1992).

The advantages of epoxies over other resins are:

- Wide range of properties allow a greater choice of selection
- Absence of volatile matters during curing
- Low shrinkage during curing
- Excellent resistance to chemicals and solvents
- Excellent adhesion to a wide variety of fillers, fibers, and substrates
The major disadvantages are:

- High cost
- Long cure time

2.5.3.2.4. Phenolics

These resins are based upon phenol (carbolic acid) and formaldehyde. However, any reactive phenol or aldehyde can be used to produce phenolic resins. Tow stage (novolac) phenolic resins are produced typically for molding convenience. In the first stage, a brittle thermoplastic resin is produced, which will not be cross-linked to form a matrix. The addition of basic catalyst is added to the above to create methylen cross-linkage. When heat and pressure are applied, the hexa group decomposes, producing ammonia, leading to methylen cross-linkage (Smith, 1990). During the cure stage, these resins produce water, which should be removed, because glass fibers will not absorb water. The temperatures for curing ranges from 2500 °F to 3500 °F. Combining the resin with various fillers makes molding compounds. The high cross-linkage of the aromatic structure produces high hardness, rigidity, and strength combined with good heat and chemical resistance properties. The special features of phenolic resins are their resistance to fire and their low toxicity, and low smoke productions under fire conditions. On comparison with all other resins in GFRP composites, phenolics are the best to matching flammability requirements (Hota, 2003).

2.5.3.2.5. Polyurethane Resins

Polyurethanes can be used in thermoset or thermoplastic form. Thermoset polyurethanes are used either to bond structural members or to increase Young’s modulus (stiffness) of structural components such as automotive bumper facias made of reaction injection molding (RIM) process. Also, polyimide resins with performance temperatures of the
order of 700 °F are available with thermoset resin formulation. Similarly polybutadine resins have been used in thin-walled glass reinforced radomes in lieu of E-glass reinforced epoxy composites. Addition of an alcohol to an isocyanate leads to a polyurethane. To obtain additional cross-linkage, i.e., to increase stiffness and cross-linking, an excess amount of di-isocyanate is used to make sure that some of the polymer chains end in unreacted isocyanate functions. The polymeric di-isocyanate reacts with urethane linkage in other polymer chains to provide extra cross-linking. If large number of cross-links are formed with cross-link chains being short and rigid, then the urethane resin can be hard with higher stiffness. Similarly, flexible urethanes can be obtained using extra amount of water for reaction and reducing isocyanate polymer.

2.5.3.3. Comparison of Thermoplastic and Thermoset Resins

Some thermoplastics are amorphous while others are semi-crystalline; whereas all thermosets are amorphous. The advantages of thermoplastic resins are:

- Excellent tolerance to damage (high impact strength and fracture resistance)
- Higher strength-to-failure ratio
- Unlimited storage life at room temperature
- Shorter fabrication time
- Postformability (e.g., by thermoforming)
- Ease of repair (by welding, solvent bonding, etc.)
- Ease of handling (no tackiness)
- Recyclability
- Higher fracture toughness and better delamination resistance under fatigue than epoxies
The disadvantages of thermoplastic resins are:

- Poor creep
- Poor thermal stability

The advantages of thermoset resins over thermoplastic resins are:

- Better creep resistance
- Improved stress relaxation
- Thermal stability
- Chemical resistance

The disadvantages of thermoset resins are:

- Low-impact strengths (low strain-to-failure)
- Long fabrication time in mold
- Limited storage life at room temperature (before the final shape is molded)

2.5.3.4. Properties of Resins

The mechanical properties of the resins are much lower when compared to the fibers. Properties of the most widely used resins are presented in Table 2-3 (Hota, 2003).
<table>
<thead>
<tr>
<th>Material</th>
<th>Flexural strength (psi)</th>
<th>Flexural elastic modulus (10^6 psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>10000 - 16000</td>
<td>0.30 - 0.50</td>
</tr>
<tr>
<td>ABS</td>
<td>8000 - 11000</td>
<td>0.25 - 0.35</td>
</tr>
<tr>
<td>PE</td>
<td>---</td>
<td>0.10 - 0.26</td>
</tr>
<tr>
<td>PP</td>
<td>6000 - 8000</td>
<td>0.17 - 0.25</td>
</tr>
<tr>
<td>PC</td>
<td>13500</td>
<td>0.32 - 0.35</td>
</tr>
<tr>
<td>Polyester</td>
<td>8500 - 23000</td>
<td>---</td>
</tr>
<tr>
<td>Epoxy</td>
<td>13300 - 21000</td>
<td>---</td>
</tr>
<tr>
<td>PF</td>
<td>7000 - 14000</td>
<td>1.0 - 1.2</td>
</tr>
<tr>
<td>SI</td>
<td>10000 - 14000</td>
<td>1.0 - 2.5</td>
</tr>
</tbody>
</table>
3. TEST SPECIMEN PREPARATION

3.1. Introduction

The wood posts are GFRP wrapped to improve their mechanical properties, i.e., strength and stiffness. The wood posts are wrapped in the center, along the longitudinal axis with GFRP wrap length equal to 20-inch (Figure 3-1). The set up for test specimen preparation (wrapping the posts) consists of a wrapping machine (Figures 3-2 and 3-3), glass fabric (12-inch wide) supported on a stand and a resin bath with a fabric guide. The glass fabric passing through the resin bath was wrapped on the post by rotating the post at constant speed. The wrapping process and machine are discussed in this chapter.

3.2. Material Selection

The types of materials used in a hybrid material (GFRP wrapped wood post) determines its mechanical properties. The types of materials used in GFRP wrapped wood posts are presented below.

3.2.1. Wood

The type of wood post used to conduct this study is called Long Leaf. This type of wood is sub-specie of Southern Pine. It is used because of its ease of availability and wide usage.

3.2.2. Fabric

The glass fiber used in the study was compatible with phenolics in the sense that fiber sizing provides better bonding compatibility with phenolic based resins than other resins. The fabric used in this study is E-glass. This is used based on its advantage over other fabrics in terms of
its cost. The mechanical properties are also relatively comparable to any other material for the given cost of the material (Anegunta, 2000, and Laosiriphong, 2000).

3.2.3. Resin

Phenolic and epoxy are the most widely used resin to bond composites to substrates made of conventional materials. The reason for their extensive use is their superior processing versatility compared to other adhesives. In addition, curing reaction for phenolic and epoxy resins does not involve release of water like other adhesives, which helps in low shrinkage and minimization of void formation during curing (Subramanian, 1981). This leads to low residual stresses and better bond strength. Hence, phenolic was chosen in this study to evaluate its compatibility with wood posts. The type of resin used is phenolic based G 1131-A. The hardener as well as catalyst used is formaldehyde based G 1131-B.

3.3. GFRP Wrapping

- The wood posts are cleaned using air pressure.
- Primer (G1131-A) was applied uniformly throughout the post using a paintbrush.
- The primed posts are allowed to cure at room temperature for at least 24 hours.
- The 1:5 ratio of G1131-B and G1131-A are mixed to obtain the resin.
- The density of glass fabric is 28 oz/sq.yd. It is saturated with the resin during the wrapping process.
• The post was GFRP wrapped at mid-span over a length of 20-inch. Two layers of 12-inch fabric are wrapped alongside with a 2-inch overlap, giving an overall length of 20-inch. The post is wrapped again (wrap over wrap) as discussed above. The GFRP wrapped post is shown in Figure 3-1.

• The glass fabric was cut to the required dimensions using scissors. The lead end of the glass fabric ran through a resin bath and was stapled on to the post. The post was rotated to wrap the glass fabric around it.

• Uniform tension (approximately 10-lb) was applied to the glass fabric using wrapping machine (Figures 3-2 and 3-3) in order to eliminate gap and air between each layer of fabric.

• After the glass fabric was wrapped, the far end of the glass fabric was stapled on to the post.

• The post was rotated and cleaned with a paintbrush to prevent dripping of resin and promote uniform curing.

• The GFRP wrapped post was cured for six (6) days at room temperature.

• These wrapped specimens are also referred to as hybrid materials, and GFRP wrapped posts in later chapters.
3.4. Horizontal Axis Wrapper (HAW)

Horizontal Axis Wrapper (HAW) is used to wrap wood posts. This machine produces a surface of revolution (cylindrical) over the post.

Components

HAW consists of the following components: 1) two gripping mechanisms (left and right), 2) resin-bath container, 3) Self-locking ratchet (Figures 3-2 and 3-3).
Figure 3-2. Horizontal Axis Wrapper (HAW) Front View

Figure 3-3. Horizontal Axis Wrapper (HAW) Side View
**Procedure**

The wood post is fixed between the two grippers. The glass fabric is pulled through the self-locking ratchet to the resin-bath container. After the fabric is saturated in the resin, it is pulled and stapled to the wood post. The wood post is revolved around its own axis using the grippers. This motion allows the resin-saturated glass fabric to wrap around the post, thus building up the laminate thickness. When the desired laminate thickness is reached, the motion is stopped. The fabric is cut and stapled to the wood post.

**Tension**

Tension is applied to the reinforcement as it is being wound onto the post. The self-locking ratchet mechanism helps keep the existing tension by preventing the machine from unwinding.

**Conformation**

The fibers conform to the post surface by virtue of the winding tension. The resin used to impregnate fibers is gluey (sticky). This helps to generate sufficient frictional force to keep the fiber on the surface of the post.

**Cure**

The GFRP wrapped posts are allowed to cure at room temperature for at least 48 hours. Heat can also be applied to accelerate the curing process to 24 hours.

**3.5. Vertical Axis Wrapper (VAW)**

A prototype Vertical Axis Wrapper (VAW) is a portable machine that was developed as a part of this research and was used for GFRP wrapping of wood posts. This machine is portable and can be used for
field applications. It produces a surface of revolution (cylindrical) around a circular wood post.

Components

VAW consists of the following components: 1) two gripping mechanisms (top and bottom), 2) a threaded steel member, 3) mobile-cylinder consisting of resin-saturated fabric (Figure 3-6), and 4) ratchet mechanism to preserve tension on the fabric (Figure 3-7).

Design of Ratchet Mechanism

A wheel provided with suitably shaped teeth, receiving an intermittent circular motion from an oscillating or reciprocating member, is called a ratchet wheel. A simple form of ratchet mechanism is shown in Figure 3-4.

![Figure 3-4 Ratchet Wheel Mechanism](image)

A is the ratchet wheel, and B is an oscillating lever carrying the driving pawl, C. A supplementary pawl at D prevents backward motion of the wheel. When arm B moves counterclockwise, pawl C will force the wheel through a fractional part of a revolution dependent upon the motion of B. When the arm moves back (clockwise), pawl C will slide over the points of the teeth while the wheel remains at rest because of fixed pawl D, and will be ready to push the wheel on its forward (counterclockwise) motion as before. The amount of maximum possible backward motion
varies with the pitch of the teeth. This motion could be reduced by using small teeth, and the expedient is sometimes used by placing several pawls side by side on the same axis, the pawls being of different lengths. The contact surfaces of wheel and pawl should be inclined so that they will not tend to disengage under pressure. This means that the common normal at N should pass between the pawl and the ratchet-wheel centers. If this common normal should pass outside these limits, the pawl would be forced out of contact under load unless held by friction.

In the ratchet mechanism used in VAW, the pawl is held against the wheel during motion by the action of a spring. The supplementary pawl at D that prevents backward motion of the wheel is integrated into pawl C. (Figure 3-7). The parts used to develop the ratchet mechanism are shown in Appendix F.

**Procedure**

The resin-saturated fabric is stapled to the post at the top (beginning of the wrap, Figure 3-5). The mobile-cylinder traverses the length of the post with the following motion: 1) rotation around the post, 2) rotation around itself, and 3) transverse motion along the steel-member. This motion allows the fabric to wrap around the post, thus building up the laminate thickness. The pitch of the steel-member is 0.25-inch. For each revolution around the post, the mobile-cylinder traverses (moves down) a length equal to twice the pitch of the steel-member, i.e., 0.5-inch. When the fibers reach the bottom of wrapping length, the motion is stopped. The fabric is cut and stapled to the post. This sequence of wrapping procedure is shown in Figure 3-5.
Figure 3-5 Wrapping Process of VAW
Figure 3-6 Vertical Axis Wrapper (VAW)
Tension

Tension is applied to the reinforcement as it is being wound onto the post. The ratchet mechanism with a spring-loaded key helps keep the existing tension by preventing the machine from unwinding (Figure 3-7). This tension results in the reinforcement applying a pressure to the post surface. This pressure effectively consolidates the laminate.

Conformation

The fibers conform to the post by virtue of the winding tension. The resin used to impregnate fibers is sticky. This helps generate sufficient frictional force to keep the fiber bonded on to the surface of the post.

Cure

The GFRP wrapped post is allowed to cure at room temperature for at least 48 hours. Heat can also be applied to accelerate the curing process to 24 hours.
4. TEST SETUP AND METHODOLOGY

4.1. Introduction

The purpose of this chapter is to describe briefly the test methods used for mechanical testing of hybrid materials (GFRP wrapped wood posts). Although many analytical models have been developed to analyze the mechanical properties (strength, stiffness, and damping) of hybrid materials (Gibson, 1994), the usefulness of such models depends heavily on the availability of measured data. In addition, some aspects of mechanical behavior are so complex that the feasibility of proper analytical modeling is questionable (Gibson, 1994). Hence, the measurement of mechanical properties is an important element in analyzing the properties of hybrid materials. The test methods used to measure stiffness (static and dynamic) and damping coefficient of (test) specimen (unwrapped and GFRP wrapped wood posts) are discussed.

4.2. Measurement of Stiffness

The stiffness of a specimen is measured using three-point test set-up (Figure 4-1) in static test conditions and Laser-Vibrometer test set-up (Figure 4-4) in dynamic test conditions. Difficulties encountered in these tests are discussed along with their limitations and possible sources of error.

4.2.1. Three-Point Bending Test Setup and Methodology

Bending rigidity (EI) of the specimen under static bending load (EI\textsubscript{st}) is determined following the ASTM D 198-99 test method. In this method, deflections of the specimen are measured at regular intervals with respect to load. EI\textsubscript{st} is then computed by solving equation 4-1.
In this study, the specimens were tested in three-point bending configuration (Figure 4-1) shown below.

![Three-Point Bending Test Set-up](image)

Figure 4-1 Three-Point Bending Test Set-up

**Supports:**

Two steel beams were used as end supports for the specimen. They provided a test-span equal to $L_e$. 
Figure 4-2 Three-Point Bending Test Set-up (Loading System)

Load:

The loading system in the test set-up consists of the following components (Figure 4-2):

- A loading jack with 50,000 lb capacity.
- A hydraulic pump to induce loads.
- A load cell calibrated to 10,000 lb prior to testing.
- A strain indicator connected to load cell to measure applied load.
Deflection:

A dial-gauge to measure deflections of test specimens is shown in Figure 4-3. It is calibrated for an accuracy of 0.001\textsuperscript{th}-inch.

Test Methodology:

- Load was applied at the geometric center of the specimen.
- Deflections below the load were taken at regular intervals with respect to load.
- Load applied was applied as a patch on half inch thick elastomatic padding.
The equation to measure EI_{st} of specimen (simply supported beam) is derived from classical mechanics (Gibson, 1994) and given by:

\[ EI_{st} = \frac{P \times L_e^3}{48 \times \delta} \]  

...4-1

where,

Load = P

Deflection = \delta

Test span = L_e

One possible limitation of using a bending test is that shear deformation can be significant unless the beam span-to-depth ratio is at least 8 (ASTM D 198-99). To reduce the shear deformation, a ratio between 8.63 and 11.45 was maintained in our test samples. The results are given in Chapter 5.

4.2.2. Laser-Vibrometer Test Setup and Methodology

EI of the specimen under dynamic excitation (EI_{dy}) is determined following the ASTM D 4065-01 test method. In this method, the natural frequencies (first and second) of the specimen are measured under induced vibration. Using either or both of the natural frequencies, EI_{dy} is computed solving the frequency equation (Blevins, 1979), equation 4-2.

In this study, the specimen was tested in a free-free boundary condition. It was suspended in a horizontal position from two rigid supports using very low-weight elastic chords with near zero bending stiffness. A shaker was used to excite the specimen while the laser beam measures the acceleration-time response (Figure 4-4). The first and second natural frequencies were excited.
The equation for the natural frequency of a single-span specimen (post) in free-free test set-up is given as (Blevins, 1979):

$$f_i = \frac{\lambda_i^2}{2\pi L^2} \sqrt{\frac{EI_{dy}}{m}}$$

for $i = 1, 2, 3...$ ...

where:

$f_i$ = $i^{th}$ natural frequency

$\lambda_i$ is $i^{th}$ coefficient (mode) wherein $\lambda_1 = 4.73, \lambda_2 = 7.853, \lambda_3 = 10.995...$

Weight of the specimen = $W$ (lb)

Length of the specimen = $L$ (in)

Acceleration due to gravity = $g = 3.22 \times 10^1 \text{ ft/s}^2$
Mass density per unit length of specimen = \( m = \frac{W}{gxL} \) (slugs/in)

Solving equation 4-2 for EI:

\[
EI_{dy} = \frac{m \times 4 \times \pi^2 \times f_i^2 \times L^4}{\lambda_i^4}
\]

One possible limitation of using vibration test is that this test does not take into account the coupling effect, transverse shear effect, and other possible peculiarities of specimen behavior. To reduce these errors, the specimens were supported in such a way as to minimize damping due to the apparatus or the test environment (used very low weight and near zero bending stiffness elastic chord in free-free test set-up). The results are given in Chapter 5.

4.3. Measurement of Damping

Damping capacity of a material can be defined as the measure of dissipation of energy. Damping can be measured using the loss factor in the complex modulus notation. There are many test methods to determine the damping capacity of a material. One forced vibration and one free vibration test method are described briefly.

Forced vibration technique is based on the variation of the excitation frequency, simultaneous measurement of the response, and plotting of the magnitude and/or phase of the response in the frequency domain. The resulting frequency response curve, or frequency response spectrum has a number of peaks which represent natural frequencies of the specimen, and curve-fitting techniques can be applied to these peaks to extract the data needed to compute the complex modulus. The storage modulus is determined by substituting the peak frequency for a particular mode into the specimen freqency equation as described previously. The loss factor may be determined by using the half power bandwith equation
\[ \eta = \frac{\Delta f}{f_n} \]

where

\( \Delta f \) = bandwidth at the half power points on the peak

\( f_n \) = peak frequency for the \( n^{th} \) mode of vibration

In a free vibration experiment, the specimen is released from some initial displacement, or a steady state excitation is removed, and ensuring free vibration decay of the specimen is observed. From this decay curve, the damping capacity of the specimen can be measured as described below.

### 4.3.1. Damping Test Setup and Methodology

Viscous damping capacity (damping capacity) of the specimen can be determined following the ASTM E 756-98 (free-vibration) test method. In this method, the successive wave amplitudes of the specimen are measured while the specimen undergoes free vibration decay. Damping capacity of a material can be characterized by its log decrement \( \delta \). Log decrement is defined as the natural logarithm of the ratio of two successive decaying wave amplitudes (\( A_i \) and \( A_{i+1} \)) for a body set in harmonic motion and allowed to vibrate freely (Gibson, 1994). This decay rate of damping is energy dissipation per cycle of vibration. For a single degree of freedom system (specimen vibrating in a single mode shape), the energy loss per cycle is a function only of amplitude. Log decrement can be obtained using equation 4-4.

In this study, the specimen was tested for log decrement using Laser-Vibrometer set-up shown in Figure 4-4. It is suspended in a horizontal position from two rigid supports using a very low-weight elastic chord. A shaker was used to excite the specimen to a steady state and subsequently released allowing it to undergo free vibration decay.
The log decrement ($\delta$) is defined as the natural logarithm of the ratio of two successive decaying wave amplitudes ($A_i$ and $A_{i+1}$) for the specimen set in harmonic motion and allowed to vibrate freely (Figure 4-5).

$$\delta = \ln(A_i/A_{i+1})$$ ...

![Figure 4-5 Free-Vibration Decay of Specimen](image)

While using a free-vibration test method, the frictional damping at specimen support points, transducer attachments, aerodynamic drag on vibrating specimen, and phase lag in instrumentation may lead to erroneous damping data. Also, logarithmic decrement values are affected by moisture content, temperature, grain direction, and frequency of vibration (the damping value should be measured for one particular mode). Typically, the values for logarithmic decrement increase as moisture content increases and as temperature decreases. In this test setup, precaution is taken to ensure that only one mode of vibration is
present in the response decay curve. To achieve this objective, the test specimen is excited to find its first natural frequency. Then, the test specimen is excited to its first natural frequency at a steady state. Finally, the test specimen is released and the vibrational response is allowed to decay. The results are given in Chapter 5 and the log decrement of unwrapped posts is verified with published data (James, 1961) in Chapter 6.
5. TEST RESULTS

5.1. Introduction

Evaluation of strength, stiffness, and damping of materials depends on the availability of mechanical data obtained through experiments. Experimental data of specimen (unwrapped and GFRP wrapped wood posts) obtained from static, dynamic and damping test methods are presented in this chapter. The numbers of posts of different diameters tested are presented in Table 5-1.

Table 5-1 Number of Posts Tested

<table>
<thead>
<tr>
<th>Test</th>
<th>Number of Posts</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unwrapped</td>
<td>Wr</td>
<td>Unwrapped</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2L</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3L</td>
<td></td>
</tr>
<tr>
<td>Static</td>
<td>26</td>
<td>17</td>
<td>5</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>12</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Dynamic</td>
<td>18</td>
<td>12</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Φ = Diameter; 2L = 2-Layer Wrapping; 3L = 3-Layer Wrapping
Table 5-2 Number of Posts Presented

<table>
<thead>
<tr>
<th>Test</th>
<th>Unwrapped</th>
<th>Wr 2L</th>
<th>Wr 3L</th>
<th>Unwrapped</th>
<th>Wr 2L</th>
<th>Wr 3L</th>
<th>Unwrapped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>13</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Dynamic</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Damping</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Φ = Diameter; 2L = 2-Layer Wrapping; 3L = 3-Layer Wrapping

The experimental data obtained from the tests are presented in this chapter. The results of these tests are discussed in Chapter 6.

5.2. Static Test Results

Thirty-four (34) unwrapped posts were tested under static test conditions as described in Chapter 4. Twenty-two (22) of the unwrapped posts were wrapped and tested again in the same test set-up. In this section, the results of 15 posts are presented. In the 3-point bending test, deflections of test specimen were measured at regular intervals with respect to load. The posts were tested within the elastic zone. The static test data are presented in Table 5-3.
<table>
<thead>
<tr>
<th></th>
<th>Φ (in)</th>
<th>L</th>
<th>Load (lb)</th>
<th>Deflection (in)</th>
<th>Test span (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Un wr</td>
<td>Wr</td>
<td>Un wr</td>
</tr>
<tr>
<td>Z1</td>
<td>4.65</td>
<td>2L</td>
<td>1477</td>
<td>0.156</td>
<td>63</td>
</tr>
<tr>
<td>Z2</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.157 0.143</td>
<td>63 63</td>
</tr>
<tr>
<td>Z3</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.167 0.151</td>
<td>63 63</td>
</tr>
<tr>
<td>Z4</td>
<td>5.75</td>
<td>3L</td>
<td>2659</td>
<td>0.196 0.152</td>
<td>63 63</td>
</tr>
<tr>
<td>Z5</td>
<td>4.65</td>
<td>2L</td>
<td>2659</td>
<td>0.250 0.210</td>
<td>63 63</td>
</tr>
<tr>
<td>Z6</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.171</td>
<td>63</td>
</tr>
<tr>
<td>Z7</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.163</td>
<td>63</td>
</tr>
<tr>
<td>Z8</td>
<td>4.65</td>
<td>2L</td>
<td>2659</td>
<td>0.281 0.237</td>
<td>63 63</td>
</tr>
<tr>
<td>Z9</td>
<td>4.65</td>
<td>2L</td>
<td>2659</td>
<td>0.409 0.330</td>
<td>63 63</td>
</tr>
<tr>
<td>Z10</td>
<td>7.30</td>
<td>0</td>
<td>4431</td>
<td>0.165</td>
<td>63</td>
</tr>
<tr>
<td>Z11</td>
<td>7.30</td>
<td>0</td>
<td>4431</td>
<td>0.164</td>
<td>63</td>
</tr>
<tr>
<td>Z12</td>
<td>7.30</td>
<td>0</td>
<td>4431</td>
<td>0.161</td>
<td>63</td>
</tr>
<tr>
<td>Z13</td>
<td>4.65</td>
<td>2L</td>
<td>2659</td>
<td>0.322 0.259</td>
<td>63 63</td>
</tr>
<tr>
<td>Z14</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.171 0.154</td>
<td>63 63</td>
</tr>
<tr>
<td>Z15</td>
<td>5.75</td>
<td>2L</td>
<td>2659</td>
<td>0.160 0.145</td>
<td>63 63</td>
</tr>
</tbody>
</table>

Φ = diameter; Un wr = Unwrapped; Wr = wrapped; 2L = 2-layer; 3L = 3-layer
5.3. Dynamic Test Results

Fifteen (15) unwrapped wood posts were tested under dynamic load conditions as described in Chapter 4. Nine (9) of the unwrapped posts were wrapped and tested again in the same test set-up. In the dynamic test, the natural frequencies of the specimen were captured from the amplitude-frequency response curve (Figure 5-1).

![Amplitude-Frequency Response Curve](image)

Figure 5-1 Amplitude-Frequency Response Curve in Dynamic Test

The screen captures of other posts are presented in Appendix A. The dynamic test data are presented in Table 5-4.
Table 5-4 Dynamic Test Results of Long Leaf (Sub-Species of Southern Pine)

<table>
<thead>
<tr>
<th></th>
<th>Φ (in)</th>
<th>Weight (lb)</th>
<th>Span (in)</th>
<th>First natural frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Un wr</td>
<td>Wr</td>
<td>Un wr</td>
<td>Wr</td>
</tr>
<tr>
<td>Z1</td>
<td>4.65</td>
<td>2L</td>
<td>31</td>
<td>83</td>
</tr>
<tr>
<td>Z2</td>
<td>5.75</td>
<td>2L</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>Z3</td>
<td>5.75</td>
<td>2L</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>Z4</td>
<td>5.75</td>
<td>3L</td>
<td>40</td>
<td>41</td>
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<td>Z5</td>
<td>4.65</td>
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<td>2L</td>
<td>22</td>
<td>24</td>
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<tr>
<td>Z9</td>
<td>4.65</td>
<td>2L</td>
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<tr>
<td>Z10</td>
<td>7.30</td>
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<td>45</td>
<td>69</td>
</tr>
<tr>
<td>Z11</td>
<td>7.30</td>
<td></td>
<td>47</td>
<td>68</td>
</tr>
<tr>
<td>Z12</td>
<td>7.30</td>
<td></td>
<td>45</td>
<td>68</td>
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<td>Z13</td>
<td>4.65</td>
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<td>Z14</td>
<td>5.75</td>
<td>2L</td>
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</tr>
<tr>
<td>Z15</td>
<td>5.75</td>
<td>2L</td>
<td>41</td>
<td>42</td>
</tr>
</tbody>
</table>

Φ = diameter; Un wr = Unwrapped; Wr = wrapped; 2L = 2-layer; 3L = 3-layer
5.4. Damping Test Results

Three (3) unwrapped posts, 3 wrapped posts and 3 damaged posts are tested for damping under dynamic test conditions as described in Chapter 4. In this test, the successive amplitudes from the amplitude-time chart are measured. The screen capture of amplitude-time chart of a specimen is shown in Figure 5-2. The screen captures of other posts are shown in Appendix D.

![Figure 5-2 Free-Vibration Decay in Damping Test](image)

The log decrement is then computed by calculating the logarithm of the ratio between corresponding amplitudes (Chapter 6). The damping test data are shown in Tables 5-5 and 5-6.
### Table 5-5 Damping Test Results of Unwrapped Posts

<table>
<thead>
<tr>
<th>Log decrement of Un wr post Z16 (%)</th>
<th>Log decrement of Un wr post Z17 (%)</th>
<th>Log decrement of Un wr post Z18 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ = 5.75-inch</td>
<td>Φ = 5.75-inch</td>
<td>Φ = 5.75-inch</td>
</tr>
<tr>
<td>4.0</td>
<td>5.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Average values based on four tests for each post

### Table 5-6 Damping Test Results of Wrapped Posts

<table>
<thead>
<tr>
<th>Log decrement of Post Z4 (%)</th>
<th>Log decrement of Post Z8 (%)</th>
<th>Log decrement of Post Z9 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ = 5.75-inch</td>
<td>Φ = 4.65-inch</td>
<td>Φ = 4.65-inch</td>
</tr>
<tr>
<td>3L wrapped Damaged 7.9</td>
<td>2L wrapped Damaged 8.2</td>
<td>2L wrapped Damaged 7.9</td>
</tr>
<tr>
<td>11.2</td>
<td>10.6</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Average values based on four tests for each post
6. ANALYSIS AND DISCUSSION OF TEST RESULTS

6.1. Introduction

Experimental and theoretical evaluations of flexural rigidity (EI) of unwrapped and wrapped posts under static and dynamic testing along with their damping properties are presented in this chapter. The experimental results are compared with theoretical results to establish their validity. In addition, the test results are discussed with respect to different parameters, i.e., test specimen property (unwrapped, 2L GFRP wrapped and 3L GFRP wrapped), static test data, dynamic test data and theoretical values.

6.2. Comparison with Theory

Static and dynamic test methods are used to determine E (Young’s modulus of elasticity) of the test specimens. The experimental static E is obtained using the load-deflection curve from bending test data (Figure 6-2) and the experimental dynamic E is obtained using frequency measurements from vibration test data. The E values obtained through the static and dynamic tests are compared with the theoretical values. The damping capacity of a wood post is measured in terms of its log decrement (logarithmic decrement). The log decrement of test specimens are obtained from vibration test data.

Static E (theoretical) for unwrapped wood post is obtained from Wood Engineering book (Gurfinkel, 1973). The dynamic E (theoretical) of unwrapped wood post is 10% more than the static E (Blevins, 1979). The E (theoretical) of a hybrid material (GFRP wrapped wood posts) is obtained by using the rule of mixtures (Mallick, 1993). The theoretical log decrement of wood posts is obtained from James (1961).
6.2.1. Static Testing

In this static test, a 3-point bending configuration is used. Assuming a perfect bond between wood, GFRP wrap, and epoxy resin, the properties of a wood/epoxy/glass specimen can be estimated using the rule of mixtures.

The following terminology and equations are used for theoretical calculations:

Unwrapped Posts

Diameter of wood post = $\Phi$

Static modulus of elasticity of unwrapped wood post = $E_{st,wd}$

The static E values of the unwrapped wood posts are obtained from Wood Engineering (Gurfinkel, 1973). The values are presented in Table 6-1.

<table>
<thead>
<tr>
<th>$\Phi$ (in)</th>
<th>$E_{st,wd}$ (lb/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.30</td>
<td>1.00 E+06</td>
</tr>
<tr>
<td>5.75</td>
<td>1.50 E+06</td>
</tr>
<tr>
<td>4.65</td>
<td>1.80 E+06</td>
</tr>
</tbody>
</table>

The moment of inertia of a wood post about its longitudinal axis = $I_{wd}$

The $I_{wd}$ value of the unwrapped wood posts is computed using:

$$I_{wd} = \frac{\Pi \times \Phi^4}{64}$$ …6-1

The $I_{wd}$ values for wood posts are presented in Table 6-2.
Table 6-2 Theoretical $I_{wd}$ of Unwrapped Posts

<table>
<thead>
<tr>
<th>$\Phi$ (in)</th>
<th>$I_{wd}$ (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.30</td>
<td>1.39 E+02</td>
</tr>
<tr>
<td>5.75</td>
<td>5.36 E+01</td>
</tr>
<tr>
<td>4.65</td>
<td>2.29 E+01</td>
</tr>
</tbody>
</table>

The theoretical $EI$ values of unwrapped wood posts are computed using the following:

$$EI_{st,wd} = E_{st,wd} \times I_{wd}$$  \(\ldots 6-2\)

The $EI$ values are presented in Table 6-3.

Table 6-3 Theoretical $EI_{st,wd}$ of Unwrapped Posts

<table>
<thead>
<tr>
<th>$\Phi$ (in)</th>
<th>Theoretical-$EI_{st,wd}$ (lb.in$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.30</td>
<td>1.39 E+08</td>
</tr>
<tr>
<td>5.75</td>
<td>8.04 E+07</td>
</tr>
<tr>
<td>4.65</td>
<td>4.13 E+07</td>
</tr>
</tbody>
</table>

Wrapped Posts:

The posts were wrapped with glass fabric saturated in resin matrix.

The number of layers of wrap is abbreviated as follows:

- $2L = 2$ layers
- $3L = 3$ layers

The thickness of each layer of wrap (in) = t
The thickness of composite wrap with different number of layers is presented in Table 6-4.

<table>
<thead>
<tr>
<th>Number of layers of wrap</th>
<th>Thickness of wrap (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The weight of the fabric used (lb) = \( W_f \)

\[
W_f = 28 \frac{Oz}{yd^2} = 28 \frac{Oz}{9 \ ft^2} = 3.11 \frac{Oz}{ft^2}
\]

Weight of 1 ft\(^2\) of fabric = \( \frac{3.11}{16} = 0.194 \) lb

Therefore, \( W_f = 0.194 \) lb

The density of the glass fibers (lb/in\(^3\)) = \( \rho_f \)

\[
\rho_f = 0.094 \frac{lb}{in^3} \quad \text{(Quinn, 1999)}
\]

The volume of glass fibers (in\(^3\)) = \( V_f \)

\[
V_f = \frac{\text{Weight(GlassFabric)}}{\text{Density(GlassFibers)}} = \frac{W_f}{\rho_f}
\]

Volume of 1 ft\(^3\) wrap (in\(^3\)) = \( V_{wr} \)

\[
V_{wr} = 12 \times 12 \times r
\]
The fiber volume fraction = $v_f$

$$v_f = \frac{Volume(GlassFibers)}{Volume(Wrap)} = \frac{V_f}{V_{wr}}$$

Modulus of elasticity of glass fibers = $E_f$

$E_f = 1.05 \times 10^7$ lb/in$^2$ (Gibson, 1994)

Modulus of elasticity of epoxy resin = $E_r$

$E_r = 4.50 \times 10^5$ lb/in$^2$ (Gibson, 1994)

Static modulus of elasticity of wrap = $E_{st,wr}$

$$E_{st,wr} = E_f v_f + (1-v_f) E_r \text{ (Classical lamination theory)} \quad \ldots 6-3$$

| Table 6-5 Steps for Calculating $E_{st,wr}$ |
|-------------------------------------------|--------|--------|
| Calculation of $E_{st,wr}$               | 2 layers | 3 layers |
| Step 1 | Thickness of wrap (in) | 1.00 E-01 | 1.50 E-01 |
| Step 2 | Weight of fabric used (Oz/yd$^2$) | 2.80 E+01 | 2.80 E+01 |
| Step 3 | Weight of fabric used (Oz/ft$^2$) | 3.11 E+00 | 3.11 E+00 |
| Step 4 | Weight of 1 ft$^2$ of fabric (lb) | 1.94 E-01 | 1.94 E-01 |
| Step 5 | Weight of fabric all layers (lb) | 3.89 E-01 | 5.83 E-01 |
| Step 6 | Density of glass fibers (lb/ft$^3$) | 9.40 E-02 | 9.40 E-02 |
| Step 7 | Volume of glass fibers (in$^3$) | 4.14 E+00 | 6.21 E+00 |
| Step 8 | Fiber volume fraction | 2.87 E-01 | 2.16 E+01 |
| Step 9 | $E$ of glass fibers (lb/in$^2$) | 1.05 E+07 | 2.87 E-01 |
| Step 10 | $E$ of epoxy resin (lb/in$^2$) | 4.50 E+05 | 1.05 E+07 |
| Step 11 | $E$ of wrap (lb/in$^2$) | 3.34 E+06 | 3.34 E+06 |
Moment of inertia of wrap (hollow GFRP wrap only) about its longitudinal axis = $I_{wr}$

$$I_{wr} = \frac{\pi}{64} \left( (\Phi + t)^4 - \Phi^4 \right)$$ \hspace{1cm} \text{...6-4}

$$E_{Ist,wr} = E_{st,wr} \times I_{wr}$$ \hspace{1cm} \text{...6-5}

EI of hybrid using the rule of mixtures:

$$E_{Ist,hb} = E_{Ist,wd} + E_{Ist,wr}$$ \hspace{1cm} \text{...6-6}

The following terminology and equations are used for analysis of experimental data:

The specimens were tested in 3-point bending configuration described in chapter 5. Each specimen was tested under a simply supported condition with $L_{eff}$ ($L_e$) as the span. The load ($P$) was acting at the geometric center of the specimen ($L_e/2$ from either support) and deflection ($\delta$) was measured below the load. The schematic diagram of the test setup is shown in Figure 6-1.

![Figure 6-1 Schematic diagram of 3-point bending test](image)
Figure 6-2 Load vs. Deflection curve in Static Test

The $E_{I_{st}}$ is computed as:

$$E_{I_{st}} = \frac{P \times L_e^3}{48 \times \delta} \quad \ldots 6-7$$

where,

Load = $P$
Deflection = $\delta$
Test span = $L_e$

6.2.1.2. Posts: $\Phi = 7.3$-inch

In this section, unwrapped wood posts with an average diameter of 7.3-inch are analyzed for $E_I$ in static testing. The theoretical and experimental results of a typical wood post (numbered Z10) are discussed below:
Unwrapped Post Z10 - Theoretical Calculations

Φ = 7.30 E+00 in

\( E_{st,wd} = 1.00 \ E+06 \ lb/in^2 \)

\( I_{wd} = 1.39 \ E+02 \ in^4 \)

\( E I_{st,wd} = 1.39 \ E+08 \ lb.in^2 \) (Theory)

Unwrapped Post Z10 - Static Test Results

\( P = 4.43 \ E+03 \ lb \)

\( \delta = 1.65 \ E-01 \ in \)

\( L_e = 6.30 \ E+01 \ in \)

\( E I_{st,wd} = 1.40 \ E+08 \ lb.in^2 \) (Static test)

Figure 6-3 Load-Deflection Curve; Φ = 7.30-inch, \( L_e = 63\)-inch (Un wr)

The \( E I_{st,wd} \) values of 7.3-inch diameter unwrapped wood posts under static test are compared with theory; the results are presented in Table 6-6.
Table 6-6 EI<sub>t</sub> of Unwrapped Posts; Φ = 7.3-inch (L<sub>c</sub> = 63-inch)

<table>
<thead>
<tr>
<th>Φ = 7.3-inch</th>
<th>EI&lt;sub&gt;st,wd&lt;/sub&gt; (No-wrap) E+08 lb.in&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory (Table 7-3)</td>
</tr>
<tr>
<td>Z10</td>
<td>1.39</td>
</tr>
<tr>
<td>Z11</td>
<td>1.39</td>
</tr>
<tr>
<td>Z12</td>
<td>1.39</td>
</tr>
<tr>
<td>Average</td>
<td>1.39</td>
</tr>
</tbody>
</table>

As shown in Table 6-6 above, the EI of unwrapped wood posts obtained using static test is similar to theoretical values. This validates the test method used to calculate static test data. These results also confirm the E (1.00 E+06 lb/in<sup>2</sup>) used to calculate the theoretical values.

6.2.1.3. Posts: Φ = 5.75-inch

In this section, unwrapped and wrapped wood posts, diameters averaging 5.75-inch are analyzed for EI in static testing. The theoretical and experimental results of a typical wood post (numbered Z4) are discussed below:

Unwrapped Post Z4 - Theoretical Calculations

Φ = 5.75 E+00 in

E<sub>st,wd</sub> = 1.50 E+06 lb/in<sup>2</sup>
\( l_{wd} = 5.36 \times 10^1 \text{ in}^4 \)

\( E_{lst,wd} = 8.04 \times 10^7 \text{ lb.in}^2 \) (Theory)

**Unwrapped Post Z4 - Static Test Results**

\[ P = 2.66 \times 10^3 \text{ lb} \]

\[ \delta = 1.96 \times 10^{-1} \text{ in} \]

\[ L_o = 6.30 \times 10^1 \text{ in} \]

\( E_{lst,wd} = 7.07 \times 10^7 \text{ lb.in}^2 \) (Static test)

**3L GFRP Wrapped Post Z4 - Theoretical Calculations**

\[ \Phi = 5.75 \times 10^0 \text{ in} \]

\[ E_{st,wd} = 1.50 \times 10^6 \text{ lb/in}^2 \]

\( l_{wd} = 5.36 \times 10^1 \text{ in}^4 \)

\( E_{lst,wd} = 8.04 \times 10^7 \text{ lb.in}^2 \)

\[ t = 1.50 \times 10^{-1} \text{ in} \]

\[ E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2 \]

\( l_{wr} = 5.82 \times 10^0 \text{ in}^4 \)

\( E_{lst,wr} = 2.04 \times 10^7 \text{ lb.in}^2 \)

\( E_{lst,hb} = 1.01 \times 10^8 \text{ lb.in}^2 \) (Theory)

**3L GFRP Wrapped Post Z4 – Static Test Results**

\[ P = 2.66 \times 10^3 \text{ lb} \]

\[ \delta = 1.52 \times 10^{-1} \text{ in} \]

\[ L_o = 6.30 \times 10^1 \text{ in} \]
EI_{st,\text{hb}} = 9.11 \times 10^7 \text{ lb.in}^2 \text{ (Static test)}

The EI values of 5.75-inch diameter unwrapped and 3L wrapped wood posts, in static test, are compared with theory; the results are presented in Table 6-7.

**Table 6-7 EI\text{st} of Unwrapped, 3L Wrapped Posts; Φ = 5.75-inch (L_e = 63-inch)**

<table>
<thead>
<tr>
<th>Φ = 5.75-inch</th>
<th>EI_{st,\text{wd}} (No-wrap) E+07 lb.in²</th>
<th>EI_{st,\text{hb}} (3-wrap) E+07 lb.in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (Table 7-3)</td>
<td>St Test</td>
<td>Theory (Table 7-3)</td>
</tr>
<tr>
<td>Z4</td>
<td>8.04</td>
<td>7.07</td>
</tr>
</tbody>
</table>
As shown in Table 6-7 above, the EI of unwrapped wood posts obtained under static testing is 12% less than theoretical values. The EI of 3L GFRP wrapped wood posts obtained under static testing is 9.6% less than theoretical values. This may be due to high value of $E$ (1.50 E+06 lb/in$^2$) used to calculate the theoretical values or lack of 100% composite action of GFRP wrap and wood post.

The theoretical and experimental results of a typical wood post (numbered Z2) are discussed below. The post has 2 layers of GFRP wrap.

**Unwrapped Post Z2 - Theoretical Calculations**

$\Phi = 5.75 \ E+00 \ \text{in}$

$E_{st,wd} = 1.50 \ E+06 \ \text{lb/in}^2$

$I_{wd} = 5.36 \ E+01 \ \text{in}^4$

$EI_{st,wd} = 8.04 \ E+07 \ \text{lb.in}^2 \ (\text{Theory})$

**Unwrapped Post Z2 - Static Test Results**

$P = 2.66 \ E+03 \ \text{lb}$

$\delta = 1.57 \ E-01 \ \text{in}$

$L_o = 6.30 \ E+01 \ \text{in}$

$EI_{st,wd} = 8.82 \ E+07 \ \text{lb.in}^2 \ (\text{Static test})$

**2L GFRP Wrapped Post Z2 - Theoretical Calculations**

$\Phi = 5.75 \ E+00 \ \text{in}$

$E_{st,wd} = 1.50 \ E+06 \ \text{lb/in}^2$
\[ I_{wd} = 5.36 \times 10^1 \text{ in}^4 \]
\[ E_{Ist,wd} = 8.04 \times 10^7 \text{ lb.in}^2 \]
\[ t = 1.00 \times 10^{-1} \text{ in} \]
\[ E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2 \]
\[ I_{wr} = 3.83 \times 10^0 \text{ in}^4 \]
\[ E_{Ist,wr} = 1.34 \times 10^7 \text{ lb.in}^2 \]
\[ E_{Ist,hb} = 9.38 \times 10^0 \text{ lb.in}^2 \text{ (Theory)} \]

**2L GFRP Wrapped Post Z2 – Static Test Results**

\[ P = 2.66 \times 10^3 \text{ lb} \]
\[ \delta = 1.43 \times 10^{-1} \text{ in} \]
\[ L_e = 6.30 \times 10^1 \text{ in} \]
\[ E_{Ist,wd} = 9.69 \times 10^0 \text{ lb.in}^2 \text{ (Static test)} \]

**Figure 6-5 Load-Deflection Curve; \( \Phi = 5.75\)-inch, \( L_e = 63\)-inch (Un wr, 2L Wr)**
The EI values of 5.75-inch diameter unwrapped and 2L wrapped wood posts, in static test, are compared with theory; the results are presented in Table 6-8.

Table 6-8 EI\textsubscript{st} of Unwrapped, 2L Wrapped Posts; \( \Phi = 5.75\)-inch \((L_e = 63\text{-inch})\)

<table>
<thead>
<tr>
<th>(\Phi = 5.75)-inch</th>
<th>(\text{EI}_{\text{st,wd}}) (No-wrap)</th>
<th>(\text{EI}_{\text{st,hb}}) (2-wrap)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory ((\text{Table 7-3}))</td>
<td>St Test ((\text{Table 7-3}))</td>
</tr>
<tr>
<td>Z2</td>
<td>8.08</td>
<td>8.82</td>
</tr>
<tr>
<td>Z3</td>
<td>8.04</td>
<td>8.29</td>
</tr>
<tr>
<td>Z14</td>
<td>8.04</td>
<td>8.10</td>
</tr>
<tr>
<td>Z15</td>
<td>8.04</td>
<td>8.66</td>
</tr>
<tr>
<td>Average</td>
<td>8.04</td>
<td>8.47</td>
</tr>
</tbody>
</table>

As shown in Table 6-8 above, the EI of unwrapped and wrapped wood posts obtained under static testing is similar to theoretical values. High E \((1.50 \text{E+06 lb/in}^2)\) is used to calculate the theoretical values. Hence these results confirm good composite action between GFRP wrap and wood post.

6.2.1.4. Posts: \(\Phi = 4.65\)-inch

In this section, unwrapped and wrapped wood posts, diameters averaging 4.65-inch are analyzed for EI in static testing. The theoretical and
experimental results of a typical wood post (numbered Z9) are discussed below:

Unwrapped Post Z9 - Theoretical Calculations

\[ \Phi = 4.65 \times 10^0 \text{ in} \]
\[ E_{st,wd} = 1.80 \times 10^6 \text{ lb/in}^2 \]
\[ I_{wd} = 2.29 \times 10^1 \text{ in}^4 \]
\[ E I_{st,wd} = 4.13 \times 10^7 \text{ lb.in}^2 \text{ (Theory)} \]

Unwrapped Post Z9 - Static Test Results

\[ P = 2.66 \times 10^3 \text{ lb} \]
\[ \delta = 4.09 \times 10^{-1} \text{ in} \]
\[ L_o = 6.30 \times 10^1 \text{ in} \]
\[ E I_{st,wd} = 3.39 \times 10^7 \text{ lb.in}^2 \text{ (Static test)} \]

2L GFRP Wrapped Post Z9 - Theoretical Calculations

\[ \Phi = 4.65 \times 10^0 \text{ in} \]
\[ E_{st,wd} = 1.80 \times 10^6 \text{ lb/in}^2 \]
\[ l_{wd} = 2.29 \times 10^1 \text{ in}^4 \]
\[ E l_{st,wd} = 4.13 \times 10^7 \text{ lb.in}^2 \]
\[ t = 1.00 \times 10^{-1} \text{ in} \]
\[ E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2 \]
\[ l_{wr} = 2.04 \times 10^0 \text{ in}^4 \]
\[ E l_{st,wr} = 7.13 \times 10^7 \text{ lb.in}^2 \]
\[ E l_{st,hb} = 4.84 \times 10^7 \text{ lb.in}^2 \text{ (Theory)} \]
2L GFRP Wrapped Post Z9 – Static Test Results

P = 2.66 E+03 lb

δ = 3.03 E-01 in

L_e = 6.30 E+01 in

E_{Ist,wd} = 4.20 E+07 lb.in^2 (Static test)

Figure 6-6 Load-Deflection Curve; Φ = 4.65-inch, L_e = 63-inch (Un wr,2L Wr)

The EI values of 4.65-inch diameter unwrapped and 2L wrapped wood posts, under static testing, are compared with theory; the results are presented in Table 6-9.
Table 6-9 EI\textsubscript{st} of Unwrapped, 2L Wrapped Posts; Φ = 4.65-inch (L\textsubscript{c} = 63-inch)

<table>
<thead>
<tr>
<th>Φ = 4.65-inch</th>
<th>EI\textsubscript{st,wd} (No-wrap)</th>
<th>EI\textsubscript{st,hb} (2-wrap)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory (Table 7-3)</td>
<td>St Test (Table 7-3)</td>
</tr>
<tr>
<td>Z9</td>
<td>4.13</td>
<td>3.39</td>
</tr>
<tr>
<td>Z13</td>
<td>4.13</td>
<td>4.30</td>
</tr>
<tr>
<td>Average</td>
<td>4.13</td>
<td>3.84</td>
</tr>
</tbody>
</table>

The difference between theoretical and static test results is because the diameter of the post is not uniform and is higher than 4.65-inch.

As shown in Table 6-9 above, the EI of unwrapped wood posts obtained under static testing is 7% less than theoretical values. This may be due to high value of E (1.80 E\textsuperscript{+06} lb/in\textsuperscript{2}) used to calculate the theoretical values. The EI of 3L GFRP wrapped wood posts obtained under static testing is 15% more than theoretical values. These results confirm good composite action between GFRP wrap and wood. It can also be stated that increase in strength due to GFRP wrapping is greater in 4.65-inch than 5.65-inch diameter wood posts.

6.2.2. Dynamic Testing

The dynamic modulus of elasticity of a beam is typically 10% more than the static modulus of elasticity of the beam (Blevins, 1979). In the dynamic test setup, a Laser-Vibrometer is used to capture vibration data. E_{dy}
(Dynamic Young’s Modulus of Elasticity) of the unwrapped/wrapped post is determined using the natural frequencies of the post as described below:

The following terminology and equations are used for theoretical calculations:

Diameter of wood post = \( \Phi \)

Static modulus of elasticity of wood post = \( E_{st,wd} \)

Dynamic modulus of elasticity of wood post = \( E_{dy,wd} \)

\[ E_{dy,wd} = 1.10E_{st,wd} \]

Moment of inertia of wood post along its longitudinal axis = \( I_{wd} = \frac{\pi \times \phi^4}{64} \)

\[ E_{l_{dy,wd}} = E_{dy,wd} \times I_{wd} \]

\( 2L = 2 \) layer

\( 3L = 3 \) layer

Thickness of GFRP wrap = \( t \)

Static modulus of elasticity of GFRP wrap = \( E_{st,wr} \)

Dynamic modulus of elasticity of GFRP wrap = \( E_{dy,wr} \)

\[ E_{dy,wr} = 1.10E_{st,wr} \] (Blevins, 1979)

<table>
<thead>
<tr>
<th>( \Phi ) (in)</th>
<th>Theoretical-( E_{l_{dy,wd}} ) (lb.in(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.30</td>
<td>1.53 E+08</td>
</tr>
<tr>
<td>5.75</td>
<td>8.84 E+07</td>
</tr>
<tr>
<td>4.65</td>
<td>4.54 E+07</td>
</tr>
</tbody>
</table>
Moment of inertia of GFRP wrap about its longitudinal axis = $I_{wr}$

$$I_{wr} = \frac{\pi}{64} \left( (\phi + t)^4 - \phi^4 \right)$$

$E_{I_{dy,wr}} = E_{I_{dy,wr}} \times I_{wr}$

$E_{I_{dy,hd}} = E_{I_{dy,wd}} + E_{I_{dy,wr}}$

The following terminology and equations are used for the analyses of experimental data:

Weight of the GFRP wrapped post = $W$

Span of the test setup = $L$

First natural frequency of the wood post = $f_1$

Acceleration due to gravity = $g = 3.22 \times 10^1$ ft/s$^2$

Mass per unit length of the wood post = $m = W/(gL)$

The equation for the natural frequency of a single-span beam in free-free test set-up is given as (Blevins, 1979):

$$f_i = \frac{\lambda_i}{2 \pi} \sqrt{\frac{EI}{m}}$$

for $i = 1, 2, 3...$

where $f_i$ = $i^{th}$ natural frequency

$\lambda_i$ is $i^{th}$ coefficient with $\lambda_1 = 4.73$, $\lambda_2 = 7.853$, $\lambda_3 = 10.995...$

Rearranging and solving for $E_{I_{dy}}$:

$$E_{I_{dy}} = \frac{m \times 4 \times \pi^2 \times f_i^2 \times L^4}{\lambda_i^4}$$
6.2.2.1. Posts: Φ = 7.3-inch

In this section, unwrapped wood posts, diameters averaging 7.3-inch are analyzed for EI in dynamic testing. The theoretical and experimental results of a typical wood post (numbered Z10) are discussed below:

Unwrapped Post Z10 - Theoretical Calculations

Φ = 7.30 E+00 in

\(E_{st,wd} = 1.00 \times 10^6 \text{ lb/in}^2\)

\(E_{dy,wd} = 1.10 \times 10^6 \text{ lb/in}^2\)

\(l_{wd} = 1.39 \times 10^2 \text{ in}^4\)

\(E_{I_{dy,wd}} = 1.53 \times 10^8 \text{ lb.in}^2\) (Theory)

Unwrapped Post Z10 - Dynamic Test Results

\(W = 4.50 \times 10^1 \text{ lb}\)

\(L = 6.90 \times 10^1 \text{ in}\)

\(f_1 = 2.26 \times 10^2 \text{ Hz}\)

\(m = 1.69 \times 10^{-3} \text{ lb.s}^2/\text{in}^2\)

\(E_{I_{dy,wd}} = 1.53 \times 10^8 \text{ lb.in}^2\) (Dynamic test)
Figure 6-7 Frequency-Amplitude Curve; $\Phi = 7.30$-inch, $L = 69$-inch (Un wr)

The $E_l$ values of 7.3-inch diameter unwrapped wood posts, in dynamic tests, are compared with theory; the results are presented in Table 6-11.

Table 6-11 $E_{ldy}$ of Unwrapped Posts; $\Phi = 7.30$-inch ($L = 69$-inch)

<table>
<thead>
<tr>
<th>$\Phi = 7.3$-inch</th>
<th>$E_{ldy,wd}$ (No-wrap) $E+08$ lb.in$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory (Table 7-10)</td>
</tr>
<tr>
<td>Z10</td>
<td>1.53</td>
</tr>
<tr>
<td>Z11</td>
<td>1.53</td>
</tr>
<tr>
<td>Z12</td>
<td>1.53</td>
</tr>
<tr>
<td>Average</td>
<td>1.53</td>
</tr>
</tbody>
</table>
As shown in Table 6-11 above, the EI of unwrapped wood posts obtained under dynamic testing is similar to theoretical values. This validates the test method used to calculate dynamic test data. These results confirms the E \( (1.10 \times 10^6 \text{ lb/in}^2) \) used to calculate the theoretical values. These results also confirms that dynamic modulus is about 10% more than the static modulus (Blevins, 1979).

6.2.2.2. Posts: Φ = 5.75-inch

In this section, unwrapped and wrapped wood posts, diameters averaging 5.75-inch are analyzed for EI in dynamic testing. The theoretical and experimental results of a typical wood post (numbered Z4) are discussed below:

**Unwrapped Post Z4 - Theoretical Calculations**

\[ \Phi = 5.75 \times 10^0 \text{ in} \]

\[ E_{st,wd} = 1.50 \times 10^6 \text{ lb/in}^2 \]

\[ E_{dy,wd} = 1.65 \times 10^6 \text{ lb/in}^2 \]

\[ I_{wd} = 5.36 \times 10^1 \text{ in}^4 \]

\[ EI_{dy,wd} = 8.85 \times 10^7 \text{ lb.in}^2 \text{ (Theory)} \]

**Unwrapped Post Z4 - Dynamic Test Results**

\[ W = 4.00 \times 10^1 \text{ lb} \]

\[ L = 7.80 \times 10^1 \text{ in} \]

\[ f_1 = 1.40 \times 10^2 \text{ Hz} \]
\( m = 1.33 \times 10^{-3} \text{ lb.s}^2/\text{in}^2 \)

\( E_{I_{dy,wd}} = 7.61 \times 10^7 \text{ lb.in}^2 \) (Dynamic test)

**3L GFRP Wrapped Post Z4 - Theoretical Calculations**

\( \Phi = 5.75 \times 10^0 \text{ in} \)

\( E_{st,wd} = 1.50 \times 10^6 \text{ lb/in}^2 \)

\( E_{dy,wd} = 1.65 \times 10^6 \text{ lb/in}^2 \)

\( I_{wd} = 5.36 \times 10^1 \text{ in}^4 \)

\( E_{I_{dy,wd}} = 8.85 \times 10^7 \text{ lb.in}^2 \)

\( t = 1.50 \times 10^{-1} \text{ in} \)

\( E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2 \)

\( E_{dy,wr} = 3.85 \times 10^6 \text{ lb/in}^2 \)

\( I_{wr} = 5.82 \times 10^0 \text{ in}^4 \)

\( E_{I_{dy,wr}} = 2.24 \times 10^7 \text{ lb.in}^2 \)

\( E_{I_{dy,hb}} = 1.11 \times 10^8 \text{ lb-in}^2 \) (Theory)

**3L GFRP Wrapped Post Z4 – Dynamic Test Results**

\( W = 4.10 \times 10^1 \text{ lb} \)

\( L = 7.80 \times 10^1 \text{ in} \)

\( f_1 = 1.65 \times 10^2 \text{ Hz} \)

\( m = 1.36 \times 10^{-3} \text{ lb.s}^2/\text{in}^2 \)

\( E_{I_{dy,wd}} = 1.08 \times 10^8 \text{ lb.in}^2 \) (Dynamic test)
The EI values of 5.75-inch diameter unwrapped and 3L wrapped wood posts, under dynamic testing, are compared with theory; the results are presented in Table 6-12.

Table 6-12 $E_{\text{Iy}}$ of Unwrapped, 3L Wrapped Posts; $\Phi = 5.75$-inch ($L = 78$-inch)

<table>
<thead>
<tr>
<th>$\Phi$ = 5.75-inch</th>
<th>$E_{\text{Iy,wd}}$ (No-wrap)</th>
<th>$E_{\text{Iy,hb}}$ (3-wrap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (Table 7-10)</td>
<td>Dy Test</td>
<td>Theory (Table 7-10)</td>
</tr>
<tr>
<td>Z4</td>
<td>8.85</td>
<td>11.09</td>
</tr>
<tr>
<td></td>
<td>7.61</td>
<td>10.80</td>
</tr>
</tbody>
</table>

Figure 6-8 Frequency-Amplitude Curve; $\Phi = 5.75$-inch, $L = 78$-inch (Un wr, 3L Wr)
As shown in Table 6-12 above, the EI of unwrapped wood posts obtained under dynamic testing is 14% less than theoretical values. The EI of 3L GFRP wrapped wood posts obtained using static test is 2% less than theoretical values. This may be due to high value of E (1.65 E+06 lb/in²) or higher value of I used to calculate the theoretical values.

Unwrapped Post Z2 - Theoretical Calculations

$\phi = 5.75 \times 10^0$ in

$E_{st,wd} = 1.50 \times 10^6$ lb/in²

$E_{dy,wd} = 1.65 \times 10^6$ lb/in²

$I_{wd} = 5.36 \times 10^1$ in⁴

$EI_{dy,wd} = 8.85 \times 10^7$ lb.in² (Theory)

Unwrapped Post Z2 - Dynamic Test Results

$W = 4.00 \times 10^1$ lb

$L = 8.50 \times 10^1$ in

$f_1 = 1.37 \times 10^2$ Hz

$m = 1.22 \times 10^{-03}$ lb.s²/in²

$EI_{dy,wd} = 9.44 \times 10^7$ lb.in² (Dynamic test)

2L GFRP Wrapped Post Z2 - Theoretical Calculations

$\phi = 5.75 \times 10^0$ in

$E_{st,wd} = 1.50 \times 10^6$ lb/in²

$E_{dy,wd} = 1.65 \times 10^6$ lb/in²

$I_{wd} = 5.36 \times 10^1$ in⁴
$E_{l_{dy,wd}} = 8.85 \times 10^7 \text{ lb.in}^2$

t = 1.00 $\times 10^{-1}$ in

$E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2$

$E_{dy,wr} = 3.85 \times 10^6 \text{ lb/in}^2$

$I_{wr} = 3.83 \times 10^0 \text{ in}^4$

$E_{l_{dy,wr}} = 1.47 \times 10^7 \text{ lb.in}^2$

$E_{l_{dy,hb}} = 1.03 \times 10^8 \text{ lb-in}^2 \text{ (Theory)}$

**2L GFRP Wrapped Post Z2 – Dynamic Test Results**

$W = 4.20 \times 10^1 \text{ lb}$

$L = 8.50 \times 10^1 \text{ in}$

$f_1 = 1.41 \times 10^2 \text{ Hz}$

$m = 1.28 \times 10^{-3} \text{ lb.s}^2/\text{in}^2$

$E_{l_{dy,wd}} = 1.04 \times 10^8 \text{ lb.in}^2 \text{ (Dynamic test)}$

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![Figure 6-9 Frequency-Amplitude Curve; $\Phi = 5.75$-inch, $L = 85$-inch (Un wr, 2L Wr)](image-url)

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The EI values of 5.75-inch diameter unwrapped and 2L wrapped wood posts, in dynamic test, are compared with theory; the results are presented in Table 6-13.

Table 6-13 $E_{I_{dy}}$ of Unwrapped, 2L Wrapped Posts; $\Phi = 5.75$-inch ($L = 85$-inch)

<table>
<thead>
<tr>
<th>Post $\Phi =$</th>
<th>$E_{I_{dy,wd}}$ (No-wrap)</th>
<th>$E_{I_{dy,hb}}$ (2-wrap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.75-inch</td>
<td>$E+07$ lb.in$^2$</td>
<td>$E+07$ lb.in$^2$</td>
</tr>
<tr>
<td>Theory</td>
<td>(Table 7-10)</td>
<td>Test (Table 7-10)</td>
</tr>
<tr>
<td>Z2</td>
<td>8.85</td>
<td>9.44</td>
</tr>
<tr>
<td>Z3</td>
<td>8.85</td>
<td>8.71</td>
</tr>
<tr>
<td>Z14</td>
<td>8.85</td>
<td>9.42</td>
</tr>
<tr>
<td>Z15</td>
<td>8.85</td>
<td>8.83</td>
</tr>
<tr>
<td>Average</td>
<td>8.85</td>
<td>9.10</td>
</tr>
</tbody>
</table>

As shown in Table 6-13 above, the EI of unwrapped and wrapped wood posts obtained under dynamic testing is similar to theoretical values. High $E$ (1.65 E+06 lb/in$^2$) is used to calculate the theoretical values. Hence these results confirm good composite action between GFRP wrap and wood post.

6.2.2.3. Posts: $\Phi = 4.65$-inch

In this section, unwrapped and wrapped posts, diameters averaging 4.65-inch are analyzed for EI in dynamic testing. The theoretical and experimental results of a typical wood post (numbered Z9) are discussed below:
Unwrapped Post Z9 - Theoretical Calculations

\[ \Phi = 4.65 \times 10^0 \text{ in} \]

\[ E_{st,wd} = 1.80 \times 10^6 \text{ lb/in}^2 \]

\[ E_{dy,wd} = 1.98 \times 10^6 \text{ lb/in}^2 \]

\[ I_{wd} = 2.29 \times 10^1 \text{ in}^4 \]

\[ EI_{dy,wd} = 4.54 \times 10^7 \text{ lb.in}^2 \text{ (Theory)} \]

Unwrapped Post Z9 - Dynamic Test Results

\[ W = 2.00 \times 10^1 \text{ lb} \]

\[ L = 7.50 \times 10^1 \text{ in} \]

\[ f_1 = 1.43 \times 10^2 \text{ Hz} \]

\[ m = 6.90 \times 10^{-04} \text{ lb.s}^2/\text{in}^2 \]

\[ EI_{dy,wd} = 3.52 \times 10^7 \text{ lb.in}^2 \text{ (Dynamic test)} \]

2L GFRP Wrapped Post Z9 - Theoretical Calculations

\[ \Phi = 4.65 \times 10^0 \text{ in} \]

\[ E_{st,wd} = 1.80 \times 10^6 \text{ lb/in}^2 \]

\[ E_{dy,wd} = 1.98 \times 10^6 \text{ lb/in}^2 \]

\[ I_{wd} = 2.29 \times 10^1 \text{ in}^4 \]

\[ EI_{dy,wd} = 4.54 \times 10^7 \text{ lb.in}^2 \]

\[ t = 1.00 \times 10^{-01} \text{ in} \]

\[ E_{st,wr} = 3.50 \times 10^6 \text{ lb/in}^2 \]

\[ E_{dy,wr} = 3.85 \times 10^6 \text{ lb/in}^2 \]

\[ I_{wr} = 2.04 \times 10^0 \text{ in}^4 \]


\[ EI_{dy,wr} = 7.85 \times 10^7 \text{ lb.in}^2 \]

\[ EI_{dy,hb} = 5.33 \times 10^8 \text{ lb-in}^2 \text{ (Theory)} \]

**2L GFRP Wrapped Post Z9 – Dynamic Test Results**

\[ W = 2.20 \times 10^1 \text{ lb} \]

\[ L = 7.50 \times 10^1 \text{ in} \]

\[ f_1 = 1.53 \times 10^2 \text{ Hz} \]

\[ m = 7.59 \times 10^{-4} \text{ lb.s}^2/\text{in}^2 \]

\[ EI_{dy,wd} = 4.42 \times 10^7 \text{ lb.in}^2 \text{ (Dynamic test)} \]

![Figure 6-10 Frequency-Amplitude Curve; $\Phi = 4.65$-inch, $L = 75$-inch (Un wr, 2L Wr)](image)

The EI values of 4.65-inch diameter unwrapped and 2L wrapped wood posts, in dynamic test, are compared with theory; the results are presented in Table 6-14.
As shown in Table 6-14 above, the EI of unwrapped wood posts obtained under dynamic testing is 10.8% less than theoretical values. This may be due to high value of $E$ (1.98 E+06 lb/in$^2$) used to calculate the theoretical values. The EI of 3L GFRP wrapped wood posts obtained using static test is similar to theoretical values. These results confirm good composite action between GFRP wrap and wood. It can also be stated that increase in strength due to GFRP wrapping is greater in 4.65-inch than 5.65-inch diameter wood posts.

6.2.3. Damping Test

Damping capacity of a material can be characterized by its log decrement $\delta$. Log decrement is defined as the natural logarithm of the ratio of two successive decaying wave amplitudes ($A_i$ and $A_{i+1}$) for a body set in harmonic motion and allowed to vibrate freely.
Values determined by James (1961) for Douglas-fir specimens, based on decay at their resonant frequency are given in Table 6-15.

Table 6-15 Log Decrement of Douglas-fir at 27 °C

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>Log decrement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5</td>
<td>2.64</td>
</tr>
<tr>
<td>23.7</td>
<td>2.63</td>
</tr>
</tbody>
</table>

The following terminology and equations are used for the analyses of experimental data:

The wave amplitudes are obtained from free-vibration decay response of a specimen (Figures 6-11 and 6-12).

Figure 6-11 Free-Vibration Decay of Post Z4; \( \Phi = 5.75 \)-inch (3L GFRP Wrapped)
Figure 6-12 Free-Vibration Decay of Post Z4; Φ = 5.75-inch (Damaged)

\[ A_i = \text{Decay amplitude of } i^{\text{th}} \text{ cycle} \]

\[ \delta = \ln \left( \frac{A_i}{A_{i+1}} \right) \]

Unwrapped Posts – Published Data

\[ \delta = 2.64\% \] (Table 6-15)

Unwrapped Posts – Damping Test Results

\[ \delta = 4.53\% \] (Table 5-4)

GFRP Wrapped Posts (2L and 3L average) – Damping Test Results

\[ \delta = 7.97\% \] (Table 5-5)

Based on the damping tests conducted on specimens (Two 2L wrapped and one 3L wrapped posts), the variation of log decrement based on number of wraps is not conclusive.
Damaged Posts – Damping Test Results

\[ \delta = 10.97\% \]  

(Table 5-5)

![Figure 6-13 Change in Log Decrement of Unwr, Wr, and Damaged Posts](image)

The log decrement of unwrapped posts in published and experimental results is different because different types of wood posts are used (Douglas-fir for theoretical and Long-Leaf for experimental results).

Between unwrapped and wrapped posts, it is observed that log decrement increased by 76%. The experimental data show that wrapping of wood posts greatly increased their damping capacity.

Between wrapped and damaged posts, it is observed that log decrement increased by 37.6%. The experimental data confirm that damaged posts have higher damping capacity than good posts.
6.3. Posts of Different Diameters Under Static Testing

The average EI of unwrapped 4.65-inch diameter posts: $4.54 \times 10^7$ lb-in$^2$

The average EI of unwrapped 5.75-inch diameter posts: $8.47 \times 10^7$ lb-in$^2$

The average EI of unwrapped 7.30-inch diameter posts: $13.9 \times 10^7$ lb-in$^2$

The EI increased by 86.5% from 4.65- to 5.75-inch diameter posts. The EI increased by 86.5% from 5.75- to 7.30-inch diameter posts. The EI increased by 206% from 4.65- to 7.30-inch diameter posts.

The average EI of 2L wrapped 4.65-inch diameter posts: $5.50 \times 10^7$ lb-in$^2$

The average EI of 2L wrapped 5.75-inch diameter posts: $9.45 \times 10^7$ lb-in$^2$

The EI increased by 71.8% from 4.65- to 5.75-inch diameter posts.

![Figure 6-14 Change of EI in static test with respect to change in diameter](image-url)
Between 4.65- and 5.75-inch diameter posts, it is observed that EI increases by 71.8% due to increase in diameter and 2L GFRP wrap, whereas 86.5% increase is noted due to diameter increase alone. These experimental data show that the variability in wood properties is high; however GFRP wrap makes the influence of variability less effective with increasing diameter of wood posts.

### 6.4. Posts of Different Diameters Under Dynamic Testing

The average EI of unwrapped 4.65-inch diameter posts: $4.69 \times 10^7$ lb-in$^2$

The average EI of unwrapped 5.75-inch diameter posts: $9.10 \times 10^7$ lb-in$^2$

The average EI of unwrapped 7.30-inch diameter posts: $15.1 \times 10^7$ lb-in$^2$

The EI increased by 94% from 4.65- to 5.75-inch diameter posts. The EI increased by 66% from 5.75- to 7.30-inch diameter posts. The EI increased by 222% from 4.65- to 7.30-inch diameter posts.

The average EI of 2L wrapped 4.65-inch diameter posts: $5.74 \times 10^7$ lb-in$^2$

The average EI of 2L wrapped 5.75-inch diameter posts: $10.3 \times 10^7$ lb-in$^2$

The EI increased by 79.4% from 4.65- to 5.75-inch diameter posts.
Figure 6-15 Change of EI in dynamic test with respect to change in diameter

Figure 6-16 Change of EI in static/dynamic test with respect to change in diameter
Between 4.65- and 5.75-inch diameter posts, it is observed that EI increases by 94% due to increase in diameter and 2L GFRP wrap, whereas 79% increase is noted due to diameter increase alone. These experimental data confirm that GFRP wrapping decreases the variability of wood properties with increase in diameter of wood posts.
7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Introduction

The primary objective of this research was to determine the effectiveness of GFRP wrapping in improving the durability and mechanical properties of CCA treated wood guardrail posts. The system under investigation was CCA treated wood that was externally reinforced with glass fibers. The conclusions drawn from the experimental results are listed below.

7.2. Conclusions

GFRP Wrapping of Posts

- Glass fibers should be saturated thoroughly in resin before wrapping.
- During wrapping of wood posts, tension (approximately 10-lb) should be applied uniformly to GFRP wrap to ensure good bond between the wrap and the post.
- During bending tests within elastic limit, there was no de-bonding between glass fabric and wood post.
- There was no de-bonding between glass fabric and wood post during exposure to very high temperature (400°F), up to 4 hours.
- There was a good correlation between EI of unwrapped and GFRP wrapped posts between experimental (static and dynamic) and theoretical results.
Static and Theoretical Testing

- Increase in static EI (experimental) of 4.65-inch diameter posts because of 2-layer GFRP wrap was 21%.
- Increase in static EI (theoretical) of 4.65-inch diameter posts because of 2-layer GFRP wrap was 17%.
- Increase in static EI (experimental) of 5.75-inch diameter posts because of 2-layer GFRP wrap was 12%.
- Increase in static EI (theoretical) of 5.75-inch diameter posts because of 2-layer GFRP wrap was 16%.
- Increase in static EI (experimental) of 5.75-inch diameter posts because of 3-layer GFRP wrap was 29%.
- Increase in static EI (theoretical) of 5.75-inch diameter posts because of 3-layer GFRP wrap was 25%.

Dynamic and Theoretical Testing

- Increase in dynamic EI (experimental) of 4.65-inch diameter posts because of 2-layer GFRP wrap was 22%.
- Increase in dynamic EI (theoretical) of 4.65-inch diameter posts because of 2-layer GFRP wrap was 17%.
- Increase in dynamic EI (experimental) of 5.75-inch diameter posts because of 2-layer GFRP wrap was 13%.
• Increase in dynamic EI (theoretical) of 5.75-inch diameter posts because of 2-layer GFRP wrap was 16%.

• Increase in dynamic EI (experimental) of 5.75-inch diameter posts because of 3-layer GFRP wrap was 41%.

• Increase in dynamic EI (theoretical) of 5.75-inch diameter posts because of 3-layer GFRP wrap was 25%.

**Static and Dynamic Testing (Experimental)**

• Increase of EI (theoretical) under dynamic testing compared to static testing was 10%.

• Increase in EI (experimental) of unwrapped 4.65-inch diameter post under dynamic testing compared to static test was 3.3%.

• Increase in EI (experimental) of 2-layer GFRP wrapped 4.65-inch diameter post under dynamic testing compared to static test was 4.4%.

• Increase in EI (experimental) of unwrapped 5.75-inch diameter post under dynamic testing compared to static test was 7.5%.

• Increase in EI (experimental) of 2-layer wrapped 5.75-inch diameter post under dynamic testing compared to static test was 8.8%.

• Increase in EI (experimental) of unwrapped 7.3-inch diameter post under dynamic testing compared to static test was 8.4%. 
Increase in EI between unwrapped and 2L wrapped 5.75-inch diameter wood posts obtained under static testing was 12% (High E, 1.50 E+06 lb/in² was used to calculate the theoretical values). The dynamic testing confirms the relative increase in EI. These results confirm that GFRP wrapping of 5.75-inch diameter posts with two layers gives good results. Good composite action between GFRP wrap and wood post was observed. These experimental data also show that the variability in wood properties was high; however, GFRP wrap makes the influence of variability less effective with increasing diameter of wood posts.

Damping Testing

- Increase in log decrement of wood posts because of GFRP wrap was 76%.
- Increase in log decrement of wood posts at failure was 37.6%.
- Good theoretical vs. experimental correlation in log decrement of unwrapped posts.

Seventy six percent increase in damping capacity (log decrement) was observed in 2-layer GFRP wrapped wood posts as opposed to unwrapped wood posts.
7.3. Recommendations

- GFRP wrapped wood posts have to be tested under fatigue, and impact to failure.
- GFRP wrapped wood posts have to be monitored for long-term field performance in terms of strain and deflection, to arrive at proper design procedures.
- Accelerated aging technique should be applied on unwrapped and GFRP wrapped posts to obtain trends in performance.
- Cost effectiveness of GFRP wrapped posts have to be evaluated after obtaining performance data over a prolonged period.
- Non-Destructive Evaluation (NDE) methods for long-term monitoring of performance of posts should be developed.
8. REFERENCES


• James, 1961 (Due to unavailability of the title of this reference, the required information is scanned and presented in Appendix G).


APPENDIX A

SCREEN CAPTURES OF DYNAMIC TESTING

Figure A-1 Dynamic Testing of Unwrapped Post Z1; Φ = 4.65-inch
Figure A-2 Dynamic Testing of Unwrapped Post Z2; Φ = 5.75-inch

Figure A-3 Dynamic Testing of 2LWrapped Post Z2; Φ = 5.75-inch
Figure A-4 Dynamic Testing of Unwrapped Post Z3; $\Phi = 5.75$-inch

Figure A-5 Dynamic Testing of 2L Wrapped Post Z3; $\Phi = 5.75$-inch
Figure A-6 Dynamic Testing of Unwrapped Post Z4; $\Phi = 5.75$-inch

Figure A-7 Dynamic Testing of 3L Wrapped Post Z4; $\Phi = 5.75$-inch
APPENDIX B

CHARTS OF DYNAMIC TESTING

Figure B-1 Frequency-Amplitude Curve of Post Z5; $\Phi = 4.65$-inch (Un wr, 2L Wr)

Figure B-2 Frequency-Amplitude Curve of Post Z14; $\Phi = 5.75$-inch (Un wr, 2L Wr)
Figure C-1 Load-Def Curve of Post Z5; $\Phi = 4.65$-inch, $L_c = 63$-inch (Un wr,2L Wr)

Figure C-2 Load-Def Curve of Post Z14; $\Phi = 5.75$-inch, $L_c = 63$-inch (Un wr,2L Wr)
APPENDIX D

SCREEN CAPTURES OF DAMPING TESTING

Figure D-1 Free-Vibration Decay Chart 2L Wrapped Post Z8; $\Phi = 4.65$-inch

Figure D-2 Free-Vibration Decay of Damaged Post Z8; $\Phi = 4.65$-inch
Figure D-3 Free-Vibration Decay of 2L Wrapped Post Z8; Φ = 4.65-inch

Figure D-4 Free-Vibration Decay of Damaged Post Z9; Φ = 4.65-inch
Figure E-1 Free-Vibration Decay Chart of Post Z8; $\Phi = 4.65$-inch
Figure E-2 Free-Vibration Decay Chart of Post Z9; $\Phi = 4.65$-inch

Figure E-3 Free-Vibration Decay Chart of Post Z4; $\Phi = 5.75$-inch
APPENDIX F

PARTS USED IN VERTICAL AXIS WRAPPER

Figure F-1 Bearing (Top View)
Figure F-2 Bearing (Front View)

Figure F-3 Housing Attached to Arm of VAW (Top View)
Figure F-4 Housed Bearing Inside Arm (Top View)
Figure F-5 Ratchet Wheel (Top View)

Figure F-6 Ratchet Wheel (Front View)
Figure F-7 Ratchet Mechanism (Top View)

Figure F-8 Ratchet Mechanism Attached to Arm of VAW (Top View)
Figure F-9 Top-Half of VAW

Figure F-10 Bottom Fixture
Figure F-11 Bottom Half of VAW
APPENDIX G

PUBLISHED DATA ON LOG DECREMENT OF WOOD

Figure G-1 Scanned Picture of Published Data on Log Decrement of Wood