ABSTRACT

Mohamed, Tarek Said. Fabrication and Behavior of Three-Dimensionally Woven Glass Fiber Reinforced Polymeric Bridge Deck. (Under the direction of Dr. Sami Rizkalla).

Deterioration of many bridge decks due to corrosion of steel triggered civil engineering researchers to consider other alternatives to the current conventional reinforced concrete and steel bridge decks. During the past two decades, researchers have intensively investigated the use of fiber reinforced polymeric (FRP) bridge decks as an alternative to the current conventional concrete and steel bridge decks. This research explored the feasibility of three-dimensional woven glass fiber reinforced bridge decks (3-D GFRP), fabricated using a textile machine and resin infusion process.

The research investigated the mechanical properties of 3-D GFRP including: Tensile properties, compression properties, and flexural properties. Three bridge decks were fabricated and tested up to failure to access the applicability of this new concept for bridge deck. The use of epoxy resin versus vinyl ester resin in the fabrication process was examined. For design purposes, the overall elastic modulus of the 3-D GFRP has been investigated using various methods.

Test results confirm the effectiveness of the proposed concept in producing bridge decks for highway bridges. The use of 3-D weaving techniques eliminates the typical delamination observed for the current pultruded GFRP bridge decks. The behavior of the 3-D GFRP bridge decks indicated promising potential, and
led to the filing of a US patent for this innovative concept in coordination with the local textile company which collaborated in providing the bridge deck.
Fabrication and Behavior of Three-Dimensionally Woven Glass Fiber Reinforced Polymeric Bridge Deck

by

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TO MY WIFE
RASHA MOHAMED
BIOGRAPHY

Tarek Mohamed was born in Alexandria, Egypt in July 1977. He received his high school diploma in the summer of 1995. In the fall of 1995, he began his undergraduate education, at the Arab Academy for Science and Technology. In June 1996, he immigrated to the United States. In the fall of 1997, he joined Auburn University, in Alabama, and received his B.Sc. Degree in Textile Engineering from Auburn University in March of 2000. Due to his great interest in research and in the composite field, he joined the College of Textiles at North Carolina State University, and received his M.Sc. Degree in Textile Engineering from North Carolina State University in August 2002.

In January of 2004, he started his Master of Science project at North Carolina State University, Civil, Construction, and Environmental Engineering Department, and expects to graduate in May of 2006.
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1. INTRODUCTION

The Federal Highway Administration has announced that approximately 40 percent of the bridges in the United States require significant rehabilitation [49]. The deficiency of those bridges is attributed to deterioration or substandard performance of their bridge decks. Repairing or replacing of these bridge decks is extremely expensive. This scenario provided the urgent needs to investigate other alternatives and/or solutions. One possible solution is the use of lightweight bridge deck to replace the existing deteriorated decks, instead of replacing the entire bridge.

Composite materials have been applied in the aerospace industry for the past few decades. In the 1980s researchers have started to investigate their applications for civil engineering infrastructure. There is a wide spectrum of advantages for using FRP for structural applications, compared to other conventional engineering materials. The advantages of these materials are: High strength to weight ratios; better corrosion resistance; flexibility to be manufactured for a variety of structural shapes; long term durability and low maintenance. Attention and concern should be given to their low modulus of elasticity; the material orthotropic and anisotropic behavior; sensitivity to temperature; and the creep rupture phenomenon.

FRP composites are mainly composed of mainly fibers and resin. Each of these constituent materials has an important role in the performance of the end product. The designer is required to select the appropriate fiber, resin and
manufacturing process based on the final application, which greatly affect the overall cost of the product as discussed in great detail in chapter 2.

Most of the current FRP bridge decks are produced by the pultrusion process. Recently, the innovative 3WEAVE® process has been used in the fabrication of bridge decks. The first generation of the bridge deck was a truss, fabricated in collaboration with textile company and tested at NC State University, in 2004 [29]. Test results indicated that the behavior is not adequate for real application of bridges. The truss configuration was selected based on the capability of the local textile company. The truss configuration is woven across the length of the machine. Therefore, to test a beam with a truss cross-section, the maximum span would be limited to six feet, which is restricted by the capability of the local textile company. The thickness of the truss was also limited by the machine and therefore did not provide sufficient stiffness required for bridge decks. The research presented in this thesis describe the use of the 3WEAVE® technology to produce a new innovative bridge deck. The selected configuration of the cross-section of the deck is hollow square section, using vertical webs to connect the top and bottom layer in compression and tension, respectively. The width and the thickness of the second generation of the 3-D GFRP were 18 inch and 4.4 inch, respectively. These dimensions were selected based on the capability of the textile machines available for this study.

1.1 Objective

The main objective of this research is to demonstrate the feasibility of using the 3WEAVE® to produce effective GFRP bridge decks. The project included
fabrication and examining of the behavior of various bridge decks with different span lengths. The FRP decks were used with and without composite action with concrete topping.

1.2 Scope

The various tasks undertaken to achieve the objective of this project can be summarized as follows:

1) Fabrication of the 3-D GFRP woven bridge deck using the available machine at the local textile company, 3TEX. The fabrication process is described in chapter 3.

2) Examine the material characteristics of the 3-D woven material using the overall behavior of the deck and small coupon specimens, as described in chapter 4.

3) Testing of three decks to examine the behavior using different span length to investigate the effect of the fiber reinforcement at the web joints, as described also in chapter 4.

4) The effect of the various resin materials that could be used for these types of application and their effect on the infusion process, are described in chapter 4.

5) Thorough review of the measured values and the material properties needed for design purposes are presented in chapter 5.

6) Summary, conclusions, and future needed research work are presented in chapter 6.
2. LITERATURE REVIEW

2.1 Fiber Reinforced Polymer

Fiber reinforced polymer, FRP, are a combination of continuous fibers and a polymer matrix. The reinforcing material must have sufficient volume in each direction to provide discernable reinforcing function in one or multiple directions. FRP composites are anisotropic (properties only optimized in the direction of the load), therefore the optimum properties are in the directions of the fibers. FRP composites are similar to reinforced concrete, where the rebar is embedded in the concrete. There are different kinds of FRP, including Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), and Aramid Fiber Reinforced Polymer (AFRP). The selection of the appropriate material depends on the desired properties of the end product and the target cost. The properties of each of these fibers are discussed in the next section.

2.2 Textile Preforms and Matrices for Composites

A “Preform” is a fabric that is manufactured into a composite material. There are four ways to manufacture performs: Weaving, braiding, knitting and nonwoven. For any of the above methods to manufacture performs, there are certain fibers that can be used in each case.

2.2.1 Reinforcing Fibers

A fiber is a unit of matter that is least 100 times longer than its thickness. The most frequently used fibers in composites are carbon, glass, aramid, and
spectra®. Carbon fibers encompass a wide spectrum of advantages including their high strength, resistance to corrosion, high heat resistance, high strength at elevated temperatures and low density. However, carbon fibers are brittle and expensive. Glass is denser than carbon and has a lower modulus. The strength and modulus of these fibers are determined by their atomic structure. Glass is divided into three types: E-glass, C-glass, and S-glass. S-glass has the highest strength. E-glass has lower cost, and has good strength and stiffness. Glass fibers are isotropic (i.e. the axial and transverse young's moduli are the same). The strength is strongly dependent on processing conditions. The diameter of E-glass ranges between 8 to 15 micrometer.

Aramid fibers consist of polyamide with benzene rings between amide groups. Aramid fibers are highly anisotropic with high strength and modulus, low density but poor transverse properties. Spectra® fibers have a linear molecular structure and high crystallinity. Spectra® fibers have a low glass transition temperature and low melting temperature. The advantages of spectra® fibers include their high strength and modulus, low density and excellent resistance to chemicals. However, several features such as poor adhesion to the matrix and high creep, due to the low intermolecular forces, prevent them from being used in many applications.

2.2.2 Matrices

The matrix material is mainly used to transfer the stress between the reinforcing fibers, holds the fibers together, and protect the fibers. Matrices are categorized into three categories: Polymeric, ceramic, and metallic. Polymeric matrices are
classified into two classes: thermoplastic and thermosetting. Thermoplastic resins do not cross-link. They have high failure strain, high impact resistance, unlimited storage life, short fabrication time, and low creep resistance. Properties of thermosetting resins depend on their molecular structure and cross-linking density. Thermosetting resins have less creep and stress relaxation, good resistance to heat and chemicals, and good wet out between fibers and matrix. However, thermosets require a long time to cure and have low impact resistance. This class of matrices includes epoxies, unsaturated polyesters, and vinyl esters. Epoxy resin is classified into two classes, prepolymer (reactive epoxy group) and cured resin (no epoxy group). During curing, epoxy react with the curing agent, known as hardener, and as curing is carried out, the molecular weight of the polymer increases as well as the glass transition temperature. There are several stages that are reached during the curing of the thermosetting resins.

2.2.3 Fabric Geometry

2.2.3.1 Basic Weaving Concept

Weaving is defined as the formation of fabric by the interlacing of the warp yarns (yarns in the X-direction) and the weft yarns (yarns in the Y-direction). Two-dimensional (2-D) weaving is a relatively high speed process. However, the fabric have an inherent crimp or waviness due to interlacing the two sets of yarns, which is disadvantage when used as performs for composites [10]. The weaving process starts by drawing the warp yarns off warp beams or creels and pass through a tensioning device to provide proper tension for the yarns for shedding. Warp yarns pass through the eyes of heddles which control the vertical
motion of the yarns during the weaving process. Each layer of yarns is raised or lowered in turn to form a shed through which the weft yarns are inserted by passing a rapier across the width of the fabric to grip the weft yarns and pull them from a weft core and back across the fabric. The weft yarns are packed tightly into the fabric by using a large “comb like” called the reed. This step is called beat-up. The shed is crossed to lock in the weft yarns and provide the interlacing. If the fabric woven is three-dimensional (3-D), the weft yarns will be inserted several times, once for each warp layer, to achieve the through the thickness reinforcement. After the last layer of weft yarns is inserted, the fabric is beat-up with the reed and the take-up mechanism pulls the preform, a certain distance, to achieve a pre-designed weft density.

Multiple insertion 3-D weaving process with multiple weft insertion at one time has been developed at the NC State University, College of Textiles and the Mars Mission Research Center. This innovation does not involve the building up of multilayer. A unit of multilayered fabric is formed during each weaving cycle. This is achieved by multiple weft insertion from one or both sides of the machine. One set of yarns feed from the back of the machine through harnesses oriented in the z or thickness direction and are called z-yarns. In this process there are warp layers, and therefore multiple shed openings for multiple weft yarns to be inserted through the width of the fabric, which results in crimp free fabric structure [3].

3TEX, Incorporated commercialized this patented technology under the trademark, 3WEAVE®. 3TEX machines now capable of producing fabrics up to
six feet wide and one inch thick. A complete review and explanation of the machine and the application of the 3WEAVE® performs in the composites industry is given in [2].

There are several advances contained within this process which include: The automated use of multiple weft insertion in one weaving cycle; the production of different shapes including “I”, “T”, and “Π” shapes; the ability to include controlled amounts of z-direction fiber (up to 30 percent of fabric volume). Additionally, any design that can be made by conventional weaving can also be made by 3WEAVE®. Moreover, due to multi-weft insertions per weaving cycle, there are some designs which can be achieved only via 3WEAVE® [1].

Machine speed is measured by the number of weft insertion actions per minute. For thicker 3-D woven designs, a 3WEAVE® machine runs slower while being more productive than a faster 2-D machine. For example, for a four warp layer fabric, a 3WEAVE® machine running at 10 weaving cycles per minute will produce at an equivalent rate to a 2-D machine running at 40 insertions per minute.

2.2.3.2 Other Preforms

The warp/weft knitting technique can also be used to produce crimp free fabrics which tows all by flat, straight, and fully extended and are subsequently knitted by fine elements to fix them in place.

Braiding performs are also being used. A braid is produced by intertwining three or more strands diagonally so that each strand passes alternately over and under
the others; 2-D braids are divided into soutache, tubular, and flat braids. 3-D braids can also be manufactured by different methods [10].

Stitching is a fairly convenient and inexpensive method for fabricating 3-D textile performs, which simply bind the fabrics, forming a 3-D construction by chain or interlock stitching of a thread structure.

2.3 Manufacturing Methods for Composites

There are many different manufacturing methods for composites ranging from hand lay-up to automated computer controlled methods. Examples of those methods include; vacuum bagging, resin transfer molding, compression molding, filament winding, pultrusion, and others.

Composite bridge decks have been under research for the past two decades. In sections 2.2.1 to 2.2.4 a few manufacturing processes are briefly described, which are adequate processes for composite bridge decks.

2.3.1 Hand Lay-up

This process is one of the oldest and perhaps the simplest method of manufacturing. It is being used to manufacture naval vessels, wing skins of military aircrafts, marine applications, and others. It is a manual process, however, in recent years computer controlled and highly automated handling equipment has been utilized into this fabrication method. The method consists of applying multiple layers of fabric and layers of resin on to a mold which corresponds to the desired shape of the composite. The advantage of this method is the ability to fabricate complex shaped composites with variable fiber
orientation and thickness. The disadvantage of this method is the demand for intensive labor and low volume production. Also, technical disadvantages which include voids, resin rich blocks, and inconsistent parts. However, the recent automation of this method reduced some of the technical problems [31].

After placing each layer of fabric, usually a roller press the fabric into the resin, and assist in wetting out the fibers with resin thoroughly and also squeeze out excess resin. Multiple layers of fabric are added and oriented to achieve the desired properties for the application. Woven, braided, knitted or stitched fabrics can be used to achieve the required thickness, strength and stiffness. Fabrics with mass/unit area of 70 oz/yd$^2$ are widely used for fabricating thick panels. Fabrics with mass/unit area of 100 oz/yd$^2$, however, wet out of the fiber could be difficult.

Different fiber orientations can be achieved in one step. Curing may take place at ambient or elevated temperatures, with or without an autoclave. Applying a vacuum and using an autoclave, results in better properties. The additional pressure forces void and excess resin outside the product (to the bleeder material) which increases the fiber volume fraction of the composite and reduce its weight. Additionally, using an autoclave permits the increase in temperature where superior properties of the resin is achieved.

It is possible to manufacture higher quality composites with prepreg materials, which are layers of fabric that are impregnated with resin then partially cured. However, prepregs normally require to be maintained at a low temperature, which limits their use.
2.3.2 Vacuum Assisted Resin Transfer Molding (VARTM)

This process combines the lay-up process, the vacuum bagging process and the resin transfer molding process, where the resin is pulled through the fibers by a vacuum. The fabric is usually placed over an open mold surface. If there is no pressure applied on the top of the specimen, then the process is called resin infusion. After the completion of the lay-up process, the mold is covered and vacuumed, then the resin is allowed to flow in the fabric from one side to another where excessive resin is drained out from the opposite side of the fabric. The mold remains sealed with vacuum applied throughout the curing process, which could be achieved at either ambient temperature or at a higher temperature which can be done in a conventional oven [31].

2.3.3 Pultrusion

This fabrication process is mainly used to produce prismatic structural members of any desired shape. This process has a relatively low cost, where continuous fibers are pulled through a resin bath, the material is then formed into the desired shape and then pulled through a heated die where the resin cures. In theory, the process is similar to the extrusion process used to manufacture aluminum [17]. The pultrusion process was developed to fabricate composite products with fibers oriented in the longitudinal direction (pulling). Composites manufactured by pultrusion usually have poor shear properties. However, in more advanced pultrusion process, pre-impregnated, stitched, woven, braided and knitted fabrics with various fiber orientations are placed into the shaper to produce composites with the desired stiffness and strength in the different directions [31].
2.3.4 Filament Winding

This process is limited to certain shapes, but more suitable for automation. A bundle of fibers are drawn through a resin bath, and then wound on a mandrel or former of the needed shape. The key parameters in this process are the fiber tension; the winding geometry and the resin take up efficiency [15].

2.4 Properties of 3-D Composites Manufactured from 3WEAVE®

3WEAVE® process and performs, one of the most promising textile processes designed to produce light weight composites with no delamination. The process is well described in [12]. The advantages of this product could be summarized to:

- Thicker fabrics, therefore less layers and less labor; faster resin infusion due to high permeability, since the z-yarns act as capillary channels which accelerates the resin into the preform; low or no fiber crimp, therefore higher in-plane properties (tension and compression);
- sufficient amount of thickness reinforcement results and total in improved inter-laminar shear strength and elimination of delamination as a failure mode; improved transverse (out of plane) strength and damage tolerance of the composites; impact performance improvements as strain rate increases from low velocity impact test to ballistic impact; the absence of interlacing between warp and weft yarns allow the fabric to bend and internally shear easily without buckling within the in-plane reinforcement.

A large serious of research has concluded that two percent by preform weight of through the thickness fiber reinforcement substantially suppress low velocity impact delamination [30].
In a research study done by Kozey, et al [8], the goal was to compare the compressive failure in 2-D and 3-D woven laminated glass/epoxy composites. The compressive failure modes were observed, the 2-D woven failed via delamination while the 3-D woven did not delaminate and exhibited a shear failure. The study concluded that 3.5 percent (by volume) fiber content in the through the thickness direction was needed to increase the composite's compressive strength. The study further proved that the fabrication technique, whether resin transfer molding or hand lay-up, have no influence on the compressive strength of the composite [8].

Another research study conducted by Wigent, et al [9] to investigate fracture and fatigue in 3-D carbon/epoxy composite. The study showed that the stress intensity required to propagate under static load ranged from 19.8 MPa m$^5$ to 29 MPa m$^5$ and a fatigue threshold yielding $10^5$ cycles was observed roughly 65 percent of the static stress intensities. This proved that the 3-D reinforcement yields advantages in durability, machinability and safety over laminated structures.

### 2.5 Stiffness Analysis of Textile Composites

The fabrication of fabrics with thickness reinforcement is possible with the use of textile processes such as braiding, weaving, and stitching. The mechanical performance of the material must be predicted by validated models. Elementary models are the simplest techniques which can predict the elastic properties of textile composites. They require little computational effort, but are unsuitable for strength analysis [31].
A unit cell is the smallest geometric entity that when repeated will reconstruct the entire reinforcement geometry. The fabric geometry model comprises a system of impregnated yarns idealized as oriented unidirectional composite rods (or lamina). The stiffness matrix for each yarn is then calculated using Hooke’s Law. The modified matrix method (MMM) with corrections and modifications introduced is limited in applications, but proved to be suitable for 3-D weave™ composites [9].

2.6 Composite Bridge Decks

In this section, summary of the published works on FRP composite bridge decks are presented. The investigations include analytical modeling as well as experimental study.

2.6.1 Switzerland

This study was conducted by U. Meier and R. Muller from the Swiss federal laboratories, in 1982. Six FRP box beams were constructed and tested under static and fatigue loading. Each beam had a length of 118 inch, thickness of 7.4 inch, and a width of 4.65 inch. The reinforcing fibers were E-glass while the matrix was epoxy. The flanges were fabricated from unidirectional lamina while the web was from two filament wound (±45°) laminates. The core of the box beams were made of epoxy resin foam. The span length was 110.24 inch. The simply supported beams were loaded at quarter spans by two actuators and by pulsators for fatigue tests [40].
For the static test, all four beams failed in the region of 33.7 to 44.96 kips in the compression flanges near the load points. Delamination occurred between the ±45° filaments and the unidirectional filaments in the compression zone, while no cracks or delamination was observed on the tension flanges [40]. Large midspan deflections were recorded for all four static load tests. The average midspan deflections under ultimate load was 5.91 inches. This study concludes that the box shape is not adequate for bridge deck, due to the large deflections occurring around the loading [40]. However, increased number of vertical webs should reduce the deflection. Optimum spacing between the vertical webs could be investigated. Ultimately, continuity of the webs could minimize the deflection.

2.6.2 Chinese Bridge

The first GFRP bridge in China was built in 1982. The bridge was built in Miyun county with a span of 66.4 feet and a roadway width of 31.5 feet. The bridge was fabricated by woven glass fabric and polyester resin using the hand lay-up technique. The bridge consists of five 69 feet long and 61 inch wide and 65.7 inch high box girders, connected to each other with GFRP. The total weight of the bridge is 80 percent lighter than a similar concrete bridge, while the construction cost was slightly higher than a concrete bridge with the same standards [41]. Static loading tests were conducted on the bridge where a 26.6 ton, a 25.7 ton, and two 15.75 ton trucks were loaded on the bridge at the same time which resulted in only 1.06 inch deflection which corresponds to span/760. Dynamic
analyses were also investigated where a 15.75 ton truck was driving back and forth on the bridge at 12 to 38 mph; the maximum deflection was 0.3 inch [42].

2.6.3 United States Army, Fort Belvoir, VA

In 1983, sets of graphite/epoxy tensile links were developed and fabricated to be used on the double story medium girder bridge (DGB). The composite links were tested at 125 kips, fatigue tested for 27000 cycles with loads of 0.5 to 115 kips. After the fatigue test, one link was loaded to failure which occurred at 230 kips. The study concluded that graphite/epoxy composite tensile elements are superior to aluminum with respect to strength, weight and stiffness.

2.6.4 Work at North Carolina State University and California State Universities

This research project was sponsored by the Federal Highway Administration in 1983, with objectives of developing a FRP composite deck system, examining both experimentally and analytically the ultimate strength and stiffness of the deck, establishing preliminary fatigue performance criteria, and developing a prototype system for connected deck panels.

The performance of five GFRP deck configurations was investigated analytically using finite element code, SAP IV. The design configurations for all decks was FRP deck behaves as a truss member in the direction perpendicular to the traffic flow, and flexural member in the direction parallel to the traffic flow. The researchers investigated two cases: Simple supported deck resting on two
stringers seven feet apart; a continuous bridge resting on five stringers seven feet apart [28].

The analytical study concluded that the best design was the X shape, shown in Figure 2.5, type 2, since it showed the lowest deflection when compared to the other four shapes.

Moreover, further modeling showed that an X-shaped deck nice inch in height, six inch in panel width, with 5/8 inch, ½ inch, and 3/8 inch thicknesses of top, bottom, and diagonal plates satisfied a deflection limit of stringer spacing/800 [28].

The X-shaped bridge deck concept which was found the best design was later fabricated experimentally using a combination of filament winding and hand lay-up processes in order to determine the static and fatigue behavior experimentally.

Filament wound E-glass/vinyl ester triangular and diamond shapes laminate were first bonded. Unidirectional tapes were then added manually. A complete description of the technique is found in [32, 33].

Three different components were studied under repeated loads; one diamond combined with two triangular sections, two diamonds combined with four triangular sections, and three diamonds combined with six triangular sections. Due to fatigue loading, all specimens experienced delamination at the interface of the unidirectional tape and the filament wound section. The fatigue tests indicated that specimens experienced stiffness loss with increasing cycles. After two million cycles, a two percent loss of stiffness was observed. When the
specimen was loaded for additional two million cycles, the loss in stiffness increased to 34 percent. The deck was subjected to fatigue loading at a load of 3.1 kips to 12.5 kips, the corresponding loss in stiffness was five percent. The deck experienced linear and elastic behavior during the loading and unloading stages.

For both simply and continuously supported boundary conditions, the X-shaped deck developed by Plecnik et al [32] was analyzed under a 7.5 kips load. Results showed that the maximum deflection was 11 percent higher than the analytical results shown by Henry et al [28].

The study showed that the damage during fatigue loading occurred primarily due to the delamination caused by inadequate interface bonding between adjacent layers within a laminate. Local buckling of the thin delaminated layers under compressive loads results in major delamination growth.

2.6.5 Work at Massachusetts Institute of Technology

Bakeri et al [34] conducted an analytical investigation. They used symmetrical lamina having a stacking of [0/60/-60], and [0/45/-45/90] to investigate a number of FRP bridge decks. The study concluded that the hybrid concept, composed of GFRP, CFRP, and light weight concrete resulted in a bridge deck system having a deflection less than S/800, where S represents the stringer spacing [34].

2.6.6 Work at University of Virginia

McGhee et al [35] used the initial study of Henry et al [28] to present results of the least weight design of four cross-section types of FRP bridge deck subjected
to 1989 AASHTO loading. These are types I, II, III, as well as a slightly modified version of type IV of Figure 2.5.

The objective was to achieve deflection smaller than S/800 and avoid local buckling. The research concluded that type III cross-section could efficiently provide an FRP deck weighing approximately 20 lb/ft\(^2\) of deck surface.

### 2.6.7 Work at West Virginia University

Gangarao et al [36] fabricated and tested two specimens of FRP bridge superstructures consisting of bridge deck and stringers. The first specimen had two exterior stringers (channels); an interior I-section stringer made from two back to back connected channels; and two solid composite plates placed on the top and bottom of the box section. The fiber direction of the solid plates was perpendicular to that of the stringers which enhanced the transverse load distribution. The second specimen used a cellular section instead of the top plate of the first specimen which improved the bending stiffness. The two specimens were loaded at the midspan of the interior and exterior stringers and at the center of a spread beam placed across the central width of the structure. Both specimens were subjected to three types of loading: concentric, eccentric, and uniform line loads. Deflection spots and strain gages were placed to monitor the bridge throughout the test. In the case of the concentric loading, it was shown that the deflection values of the outside girders differed from each other by approximately 64 percent. This may be due to experimental error.
2.6.8 Work at University of California at San Diego

Karbhari et al [37] tested eight different FRP bridge decks with different configurations and core structures, shown in Figure 2.6. The decks were fabricated using pultrusion, hand lay-up, and resin transfer molding techniques. The specimens were three to fifteen feet long and nine inches deep. The decks were tested and compared to steel reinforced concrete. The study concluded that the FRP decks experienced much higher failure loads than the steel reinforced concrete, and the FRP deck was three times lighter than the reinforced concrete deck.

2.6.9 Other FRP Bridge Decks

Lopez-Anido et al [38, 39] presented the experimental characterization of a cellular FRP H-shaped bridge deck with multiaxial fiber architecture. The deck consisted of pultruded hexagonal tubes and double trapezoidal sections bounded by adhesives, shown in Figures 2.7 and 2.8. The deck was made of E-glass triaxial stitched fabrics (±45°/90°) with binderless chopped strand mats and vinyl ester resin matrix. The fabrics were manufactured by Brunswick Technologies Incorporated (BTI). The dimensions of the specimen were eight inch deep, 45 inch width, and 108 inch span, and fabricated by VARTM. Two types of loading were applied to the panels: A patch load ten inches by 20 inch with the larger dimension perpendicular to traffic flow to simulate the action of the wheel load; and a transverse line load with a width of 11.5 inch. Each panel was loaded up to 90 kips while strains and deflections were measured on the top and bottom surfaces. The predicted flexural rigidity of the FRP bridge deck was 74,500 kip-in.
Using finite element analysis, ANSYS program was utilized to predict the
deflections and strains, the authors illustrated that they were able to obtain a
close relation with the experimental results: four to nine percent error with the
deflection and 2.4 to 33 percent error for the strains.
The authors reported that the deck did not experience stiffness loss due to
fatigue. The design of the FRP H-decks is controlled by deflection limit states.
The H-deck met AASHTO requirements for highway bridges.
Zureick et al [15] performed an analytical study using finite element analysis, on
FRP deck panels with box-shaped, shown in Figure 2.9. The dimensions of the
model were 11 inch depth, eight feet length (traffic direction). Each panel was
simply supported with a 40 feet span and subjected to one “wheel line” of an
AASHTO HS20-44 truck. Zureick modeled using material properties of E-
glass/vinyl ester and fiber volume fraction of 45 percent. The author studied four
different configurations with various fiber orientations. He found that the box-
shaped deck and the V-shaped deck were the most efficient sections. Zureick
further fabricated and tested samples following his designs at ten feet and 12 feet
stringer spacing, neither of the deck configurations were able to meet the
deflection limit of span/800.
Harik et al [20] tested FRP decks manufactured by Creative Pultrusions. The
panels consisted of double trapezoid and hexagonal pultruded components
bonded and interlocked. The depth and width of all panels were eight and 36
inch, respectively. The spans of the panels were 86, 120 and 144 inch.
The test was divided into four parts. The first part was to load the specimen from zero to 22 kips (AASHTO standard HS20) and unload back to zero to establish a baseline.

The second part was to load the specimen from zero to 22 kips (service load for an HS25 truck) and unload to back to zero. The third part was to load the specimen again from zero to 32 kips (service load for an HS30 truck) and unload back to zero; this was repeated five times. The forth part was to load the specimen from zero until failure.

The deflections were compared with the allowable deflection limits. It was found that all the FRP deck panels satisfied the deflection limits with a factor of safety of five. However, it is to be mentioned that at failure of the deck, delamination of the panel at the end of the section was observed, as shown in Figure 2.11. This was due to the lack of continuity of axial fiber along the top or bottom surfaces of the deck.

2.6.10 First Generation of 3-D GFRP Bridge Deck Manufactured Using 3WEAVE® Fabric

Norton et al [29] fabricated and analyzed two GFRP bridge decks using 3WEAVE® technology. Both decks consisted of truss configuration along the span. The first deck was 40 inch span, 15 inch width and 3.5 inch depth (Deck 1), while the second deck was 41 inch span, 15 inch width and 4 inch depth (Deck 2). Triangular Balsa cores were used to fill the triangles of the truss. Each deck was infused with epoxy resin and concrete was casted on the top. The shear connectors used were different for each deck. Static test was performed on both
decks to investigate the stiffness and strength of each deck. The stiffness tests comprised loading and unloading the deck in an increment of two kips up to 22 kips while the strength test consisted of loading the deck until failure.

Three skins were being woven simultaneously for 16 picks, then the core only was being woven additional 16 picks (to provide the extra length needed to assemble the truss). The take-up system was reversed 2.3 inch (the equivalent distance of the 16 picks woven for the core only). The core skin was connected with the top skin by two picks. Therefore the total is 50 picks that were followed by an additional 50 picks which ends with the connection of the core skin with the bottom skin. Therefore the 100 picks cycles were repeated to produce the truss configuration. The total depth of the deck was 1.25 inch.

The infusion system comprised vacuum bag infusion above a flat steel table. Metal plates were bent and devised as shear connectors for the composite bridge deck. Epoxy resin (manufactured by Jeffco Products) was used for infusion. The total depth of the deck after infusion was 1.5 inch.

QUIKRETE® 5000 concrete was casted atop the deck. It achieved 3500 psi after seven days. Two inches depth of concrete was casted atop the deck. Therefore the total depth of the deck was 3.5 inch.

The weaving process was used to produce a second deck which resembles to the weaving of the first deck except that the fabric skins were spaced out by 2.5 inch to achieve the three inch total depth needed for the deck after infusion. The triangular balsa cores were inserted as the weaving cycle was taking place.
The infusion process of the second deck was similar to the first deck except that the shear connectors were different. 3-D woven fabric 270 oz/yd$^2$ was cut into strips and nailed along the top of the truss preform. Those strips were added as shear connectors and were infused with the preform.

SikaTop® 122 Plus polymer concrete was casted atop of the second deck. It achieves 5500 psi after seven days. The total thickness of the concrete topping was one inch. Therefore the total depth of the second deck was four inch. Figure 2.12 shows a photo of the second deck prior to loading.

The truss configuration panels require extensive depth in order to achieve the desired stiffness. Therefore, the 3.5 inch depth, tested by Norton et al [29] exhibited excessive deflections, more than specified by AASHTO specifications. The shear connectors used by Norton, et al [29] were not high enough to prevent the delamination of the concrete from the FRP. Therefore, it is to be mentioned that panels did not undergo material failure. Therefore, the true strength of the panel was not determined.

The application of the innovative 3WEAVE® composites as a bridge deck is worth to be further investigated.
Figure 2.1 Schematic Diagram of 2-D Weaving Fabric

Figure 2.2 Schematic Diagram of the Innovative 3WEAVE® Design [12]
Figure 2.3 Schematic Diagram of 3WEAVE® Fabric [12]

Figure 2.4 VARTM Process, Three Different Preforms of E-glass: Plain Weave, Warp Knitted, and 3WEAVE® (on right) [1]

(a) Flow starts shortly after vacuum starts

(b) 3WEAVE® preform completely wet out before the other two performs were half filled
Figure 2.5 Cross-Sections Analyzed by Henry, et al [28]
Figure 2.6 Matrix of Specimens Tested by Karbhari [37]
Figure 2.7 Cross-section with Dimensions Illustrating Hexagonal Tubes and Trapezoidal Sections of FRP Bridge Deck from West Virginia University [38, 39]

Figure 2.8 Cross-section Illustrating Elements of Hexagonal Tubes and Trapezoidal Sections of FRP Bridge Deck from West Virginia University [38, 39]
Figure 2.9 Cross-sections of the Four FRP Panels Analyzed by Zureick et al [15]

Figure 2.10 36 inches Wide FRP Deck Tested by Harik et al [20], Produced by Creative Pultrusions
Figure 2.11 Delamination at the End of the Section of the FRP Deck Panel Tested by Harik et al [20]

Figure 2.12 Setup for Three-Point Bending Test for the 3WEAVE® FRP Deck Panels Tested by Norton, et al [29]
3. FABRICATION OF THE 3-D WOVEN GFRP BRIDGE DECKS

This chapter briefly describes the material and the fabrication process used for the fabrication of the second generation of the 3-D woven GFRP decks examined in this research.

3.1 Materials Used

The materials used in the fabrication process are:

- E-glass yarns, names Hybon® 2022 roving from PPG Fiber Glass.
- Epoxy system for infusion, named Jeffco 1401-21/4101-21, from Jeffco Products.
- End grain balsa core sheets, from Alcan Baltek Corporation.
- Ultra high molecular weight polyethylene (UHMWPE) used as a flat surface for infusion.
- Peel ply cloth, from AirTech International, Incorporated, to protect the 3-D GFRP when removing the vacuum bag after curing.
- Flow media, from AirTech International, Incorporated to assist the resin to flow into the 3-D GFRP preform.
- Vacuum bag from AirTech International.
- Breather cloth strips, to stop excess resin on the sides.
- BFLA 5.8.3L strain gages, from Texas Measurements Group.
3.2 Fabrication Processes

The main objective of this study is to provide a thorough understanding of the behavior of the 3-D GFRP beam under an equivalent load to wheel load of typical AASHTO truck load. Three bridge decks were manufactured. The width of all decks was trimmed to 18 inch. Deck 1 was four ft span and contained six z-yarns per joint; Deck 2 was also four ft span and contained 12 z-yarns per joint; Deck 3 was seven ft span and contained 12 z-yarns per joint. Therefore, Deck 1 and 2 were designed to investigate the overall performance, and also to investigate the influence of the number of fiber reinforcement needed at the joints; while Deck 3 was designed to investigate the flexure performance of typical bridge deck. All three decks were tested in three point bending, and the load was applied using 220 kips MTS actuator, at the Constructed Facilities Laboratory of North Carolina State University.

Fabrication of 3-D woven GFRP deck included three distinct processes. The fabrication was conducted at the local textile company, 3TEX, Incorporated in Cary, North Carolina. The three processes are the weaving process, the deck assembly, and the resin infusion process.

3.2.1 Weaving Process

All of the necessary fabrics needed for manufacturing the bridge decks were woven by the available weaving equipment at the local research textile company. The 3-D weaving process was discussed in detail in chapter 2. This section explains the particular setup and fabric design used to manufacture the 3-D GFRP bridge decks.
The different parts of the weaving machine are shown in Figure 3.1 and 3.2. The reed of the machine contains seven dents per inch, with a total of 137 dents. Two skins were being woven simultaneously at the same time as two separate layers, connected together with additional z-yarns (joints) every four inch. Each layer of fabric contained 411 warp yarns (3 per dent). Four filling yarns were inserted simultaneously; the top two wove the top layer, while the bottom two wove the bottom layer, as shown in Figure 3.2. The machine was computer controlled; an existing program was modified to produce fabric with six picks per inch (six Y-yarns per inch in the span direction). Each layer contained 136 z-yarns (1 per dent), divided into two harnesses as shown in Figure 3.1. Each layer was woven by two harnesses, while two additional harnesses connected both layers at the joints. Therefore, the additional harnesses contained only the additional z-yarns used to form the joints.

The fabric was designed to achieve 70 percent fiber weight fraction in the X-direction (span direction), 25 percent fiber weight fraction in the Y-direction, and 5 percent fiber weight fraction in the Z-direction. This was achieved as follows: X-yarns were selected to be 103 yds/lb, which is equivalent to 3,708 inch/lb; Y-yarns were selected to be 330 yds/lb, which is equivalent to 11,880 inch/lb, and Z-yarns were selected to be 675 yds/lb, which is equivalent to 24,300 inch/lb.

To calculate the fiber weight fraction in each direction, consider a square fabric 18 inch length by and 18 inch width:
Therefore, the number of yarns in the X-direction is 78 yarns (3x7x18); where the 3 represents three X yarns per dent, the 7 represents seven dents per inch, and the 18 represents the width of the fabric.

The number of yarns in the Y-direction is 432 yarns (4x6x18); where the 4 represents the four insertions simultaneously, the 6 represents the six picks per inch, and the 18 represents the width of the fabric.

The number of yarns in the Z-direction is 150 ([7x18] + 24); where the 7 represents seven dents per inch, the 18 represents the width of the fabric, and the 24 are the additional z-yarns at the joints (6 per joint).

The total linear length of all yarns can be calculated as the product of the number of yarns in each direction by the length of 18 inch; for the z-yarns an additional multiplication factor of 1.25 is added, since the z-yarns are going up and down (through the thickness). This factor depends on the number of picks per inch and on the weaving tension.

Therefore, the linear length of the yarns in the X-direction is 6,804 inch (18x378).

The linear length of the yarns in the Y-direction is 7,776 inch (18x432).

The linear length of the yarns in the Z-direction is 3,375 inch (18x150x1.25).

The weight of fibers in the X-direction is 29.36 oz \( \frac{6,804 \times 16}{3708} \).

The weight of the fibers in the Y-direction is 10.47 oz \( \frac{7,776 \times 16}{11,880} \).

The weight of the fibers in the Z-direction is 2.22 oz \( \frac{3,375 \times 16}{24,300} \).

Therefore, the total weight of the 18 inch by 18 inch square fabric is 42.05 oz.
Therefore, the weight fraction of the fibers in the X-direction is 69.8 percent, in the Y-direction is 24.9 percent, and in the Z-direction is 5.3 percent. Therefore, the amount of reinforcement in each direction can be controlled by the number of yarns used, the spacing between the yarns (for the X-yarns depends on the number of dents per inch of the reed), and the thickness of each individual yarn.

A q-basic computer program controlled all the weaving steps. However, the machine used was prototype and the process was not automated, which caused each step in the weaving cycles to be entered manually.

3.2.2 Deck Assembly

The second step in the manufacturing processes was the deck assembly. After all the fabrics were woven, a length was cut from the machine equal to the length of the span and an additional one foot to provide sufficient bearing length during testing, as shown in Figure 3.3.

The deck consists of two identical chords of fabric. The top layer only of the bottom chord was cut at each of the four joints and folded up to the vertical position to represent one component of the four webs. The bottom layer of the top chord was also cut at each of the four joints and folded down to the vertical position to represent the second component of the four webs; therefore, provide full overlap between the components of the webs and therefore increase the shear resistance of the deck. Therefore, only one layer of fabric was left at the bottom and the top skin of the deck. Therefore, both skins are located at an
optimum distance from the neutral axis to enhance the flexural stiffness of the
deck. The cross-section of the deck is shown in Figure 3.4.
The gaps were filled with four inch super light grooved balsa wood. Two pieces of
two inch high balsa were bonded and inserted in the deck. The contribution of the
balsa to the stiffness of the bridge deck was minor, since the strong direction of
the balsa is perpendicular to plane (depth direction). The primary function of the
balsa wood was to fill in the gaps between the fabrics and therefore, minimize the
amount of resin used in the infusion process. The balsa wood also provided a
secondary function which was to prevent buckling of the 3-D GFRP skin in
compression. Figures 3.5 through 3.8 show the process used in assembly of the
deck.

3.2.3 Resin Infusion Process

After all the fabrics were woven and the decks were assembled; the third and
final step in the manufacturing process was the resin infusion process.
The first step in the infusion process is to determine the amount of the resin
needed to completely wet out the fabric preform. The actual dimensions of Deck
1, before the final trimming to the desired dimensions, were 6.5 feet length, and
20 inch width. The weight of the deck was 58.4 lbs, therefore, for a target fiber
volume fraction of 60 percent, the amount of the matrix material needed was 39.3
lbs of resin. It is to be mentioned that the actual fiber volume fraction in this
design was expected to be less than 60 percent due to the overlapping of the
webs, which resulted in some gaps.
The resin system used for infusion was Jeffco 1401-21/4101-21. The mix ratio of
this system was 100 parts resin: 30 parts hardener, by weight. Therefore, the
39.3 lbs of matrix material was divided to 30.2 lbs resin and 9.1 lbs hardener.
The infusion surface was made of UHMW. The dimensions of the surface was
ten feet length, four feet width, and one inch thickness.
A 1/8 inch thick High Density Polyethylene (HDPE) was placed underneath the
deck to protect the infusion surface. Peel ply fabric was cut to the dimensions of
the deck and placed on the top of the deck, to separate the deck from the
vacuum bag. Red flow media was cut and placed on the top of the peel ply to
assist the resin to flow into the deck preform. Spiral tube was placed on the top of
the flow media, along the centerline of the deck along the length direction. The
resin flowed in to the inlet tube to the spiral tube.
The vacuum bag was cut to length of 11 ft (the extra length was to form pleats
along the length of the deck to eliminate gaps between the deck and the bag at
the edges, when vacuum is applied, due to the depth of the deck).
White breather material was cut into small strips and placed on the sides of the
deck, this acted like brakes to stop the excess resin and carry it to the outlet
hose.
Double sided tacky tape was placed on the surface surrounding the entire deck.
A small hole was placed in the center of the vacuum bag, where the inlet tube
was connected. Tacky tape was gently wrapped around the tube to eliminate any
possible air leaks once the vacuum is activated. An outlet tube was placed at the
center of one side of the deck where all the excessive resin was collected.
The vacuum pump was connected to the outlet tube. A clamp was placed on the inlet tube and vacuum was activated to an initial value of two inch of Mercury. The vacuum bag was arranged to eliminate any wrinkles as the vacuum was applied. After all air leaks are eliminated, the vacuum was raised to a value of 27 inch of Mercury (13.5 psi) and maintained throughout the entire process until the matrix material was completely cured.

The deck preform was preheated up to 77ºF, using an electric blanket, for two hours to enhance the curing process. When the infusion setup was completed, the next step was to weigh and mix the resin with the hardener. The resin and hardener were mixed gently for several minutes using an epoxy drill at a low speed to avoid the formation of air bubbles.

The clamp on the inlet tube was removed and the inlet tube was placed in the resin batch. The vacuum, connected to the outlet tube, was activated and the resin was pulled from the inlet tube into the deck. The duration of the infusion process was approximately 45 minutes. The gel time of the resin system should always be higher than the anticipated time needed to complete the wet out of the preform to ensure that the resin will continue to flow quickly.

The inlet and outlet tube were clamped to maintain vacuum throughout the curing process. The deck preform was covered with the electric blanket to maintain a curing temperature of 77ºF or higher for 18 hours. The deck was further post-cured at 150ºF in an oven for four hours, as recommended by the manufacturer, for optimum properties. Figures 3.9 through 3.12 show the steps taken for the infusion of Deck 1.
The deck preform was demolded from the vacuum bag and the infusion surface; excessive edges were cut, leaving the deck with final dimensions of five feet length, 18 inch width, and 4.4 inch deep.

The actual dimensions of Deck 2, before the final trimming to the desired dimensions, were 5’3” length, and 20 inch width. The weight of Deck 2 was 47 lbs. Therefore, the amount of resin needed was determined to be 24.1 lbs, and the amount of hardener needed was 10.2 lbs, following the same steps explained for Deck 1.

Infusion of Deck 2 was similar to infusion of Deck 1. The infusion setup for Deck 2 is shown in Figure 3.13

The actual dimensions of Deck 3 were, before the final trimming to the desired dimensions, nine ft long, 20 inch width. The weight of Deck 3 was 77 lbs. Therefore, the amount of resin needed was 39.5 lbs and the amount of hardener needed was 11.8 lbs. The infusion setup for Deck 3 is shown in Figure 3.14

### 3.3 Fabrication of 3-D GFRP Sandwich Panels

The objective of this study is to compare the performance of a sandwich panel infused with epoxy resin versus sandwich panel infused with vinyl ester resin. It should be mentioned that the cost of the epoxy resin and its hardener is approximately double the cost of the vinyl ester resin and catalyst. Since the amount of matrix material needed to infuse a bridge deck is large, the results of this study could significantly affect the overall cost of the 3-D GFRP deck. On the other hand, for optimum results, epoxy resin requires elevated temperatures for
post curing, which is believed to be not practical for the fabrication of bridge decks, while vinyl ester cures at room temperatures.

Fabrication of the sandwich panels took place at 3TEX in Cary, North Carolina. The top and bottom skins of each panel were made of a layer 3WEAVE® fabric 96 oz/yd². The core was two inch balsa wood.

Two panels were fabricated; Panel 1 was infused with epoxy resin system, Jeffco 1401-21/4101-21 (same system used to infuse the three bridge decks). Panel 2 was infused with vinyl ester resin system, AME 6000-35, and the catalyst used was Lupersol DDM-9, from Ashland Chemical. The mix ratio was 100 parts resin: 2 parts catalyst.

The infusion process was identical to the process used to infuse the bridge decks, except that the resin flowed from one side of the panel to the other side as shown in Figure 3.16. Since the depth of the panels was only 2.2 inch, there was no need to place the inlet tube in the middle of the top skin. A layer of nonwoven fabric was placed between each fabric skin and the core to enhance the bond between the skins and the core. Figure 3.15 shows the infusion set up for Panel 1, and Figure 3.16 shows the infusion setup of Panel 2. A summary of the panels’ infusion process is presented in table 3.1. The duration of the infusion process for Panel 1 was 15 minutes, while for Panel 2 was five minutes.
Table 3.1 Summary of Sandwich Panels Infusion Process

<table>
<thead>
<tr>
<th>Panel</th>
<th>Resin Used for Infusion</th>
<th>Dimensions</th>
<th>Mass of Top and Bottom Fabric Skins (lbs)</th>
<th>Mass of Resin (lbs)</th>
<th>Mass of Hardener or Catalyst (lbs)</th>
<th>Time Taken to Complete Infusion (minutes)</th>
<th>Curing Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Epoxy</td>
<td>4’ Length 10” Width 2.2” Depth</td>
<td>18</td>
<td>9.2</td>
<td>2.76</td>
<td>15</td>
<td>18 hours at 77ºF + 4 hours at 150ºF</td>
</tr>
<tr>
<td>2</td>
<td>Vinyl Ester</td>
<td>4’ Length 10” Width 2.2” Depth</td>
<td>18</td>
<td>11.8</td>
<td>0.236</td>
<td>5</td>
<td>24 hours at room temperature</td>
</tr>
</tbody>
</table>
Figure 3.1 3-D Weaving Machine Used for Fabrication of the Bridge Decks

Figure 3.2 Side View of the 3-D Weaving Machine
Figure 3.3 3-D Woven Fabric

fabric being cut to during the weaving process

Y yarns (6 per inch of width)

4.65”

0.4”

....

4”                                            0.65”

....

1.225”

0.2”

18”

Figure 3.4 Deck Cross-Section

Overlapping Webs

Balsa cores

Z-joints

3-D GFRP skin

Note: Not to scale
Figure 3.5 Cutting of One Layer at the Joint

one chord of the deck

wood spacer to separate both layers before cutting the top layer at the joint

Figure 3.6 Bottom Chord of the Deck with Balsa Cores Inserted

notch in the balsa for the joints
Figure 3.7  Folding the Outer Part of Both Chords

Figure 3.8  Cross-Section of Assembled Deck
Figure 3.9 Infusion Setup for Deck 1

double sided tacky tape

outlet tube, where vacuum is connected

vacuum bag

UHMW infusion surface

inlet tube

red flow media

Figure 3.10 Preheating of Deck 1 Preform with a Heating Blanket to a Temperature of 77°F
Figure 3.11 Resin Starting to Flow from the Inlet Tube into the Deck Preform

resin flows from the inlet tube into the spiral tube across the length of the deck

Figure 3.12 Resin Infusion Process Completed for Deck 1
Figure 3.13 Infusion Setup for Deck 2

Figure 3.14 Infusion Setup for Deck 3

Styrofoam oven used to post-cure all the decks
**Figure 3.15** Infusion Setup for Panel 1

- Top skin fabric
- Bottom skin fabric
- Balsa core (2 inch depth)
- Inlet tube
- Outlet tube
- Double sided tacky tape
- Resin flows from left to right
- Steel infusion table

**Figure 3.16** Infusion Setup for Panel 2

- Inlet tube
- Outlet tube
- Double sided tacky tape
- Resin flows from left to right
- Steel infusion table
4. EXPERIMENTAL PROGRAM

The behavior of the proposed 3-D GFRP bridge deck and the material characteristics used was investigated experimentally. The experimental program consisted of three phases:

- Phase I: Investigation of the limit state behavior of 3-D GFRP bridge decks under the effect of static loading conditions.
- Phase II: Study the effect of the resin used for the infusion process.
- Phase III: Determine the material characteristics of the 3-D GFRP based on measured overall behavior of the decks and the coupon specimens.

4.1 Phase I: Behavior of the 3-D GFRP Bridge Decks

A total of three 3-D GFRP bridge decks were tested. The first two decks were four feet span while the third deck was seven feet span. All decks were infused by epoxy resin and tested in three point bending using an MTS actuator.

4.1.1 Test Setup and Loading Cycles

All decks were tested in three-point bending configuration and the load was applied using a 220 kips MTS actuator. The load was applied using displacement controlled loading at a rate of 0.1 in/min. The load was applied in an increment of two kips up to 22 kips, which is an equivalent load to one wheel of an HS20 truck load according to AASHTO specifications. The deck was unloaded, and reloaded up to 26 kips, which is an equivalent load to one wheel load of an HS25 truck load according to AASHTO specifications. The deck was unloaded, and reloaded again up to 32 kips, which is an equivalent load to one wheel load of an HS30
truck load according to AASHTO specifications. The deck was unloaded, and reloaded finally to failure. Deflection was evaluated at each stage. This cyclic loading scheme was used to identify any possible permanent deformation at each loading stage.

4.1.2 Instrumentation

This section describes the instrumentation used for all three decks. Three string potentiometers were used at the centerline of the deck along the Y-direction to measure the deflection. An average value was used to represent the midspan deflection. Two string potentiometers were also placed at the quarters span. Two additional potentiometers were placed at both ends above the supports, at the compression side of the deck, to measure the deflection of the neoprene pad supports. Therefore, the net deflection at midspan and quarter points was determined.

One strain gage was attached to the outer surface of the tension side of the deck, oriented in the X-direction and one additional strain gage was attached to the compression side at six inches from the applied load. Two additional strain gages were used for Deck 3 attached to the tension and the compression side in the transverse direction, to determine Poisson’s ratio in tension and in compression. Deck cross-section and the test set up for the three tested decks, including the instrumentation used are shown in Figures 4.1 through 4.4.
4.1.3 Behavior of Deck 1

Deck 1 has a span of 48 inch, width of 18 inch, and height of 4.4 inch. All the joints had six z-yarns each, connecting both layers of the fabric together. The deck sustained 14 cycles of loading, with an increment of two kips, before failure. The deck experienced pre-mature failure due to separation of the webs from the bottom skin at the joints, as shown in Figure 4.5. This behavior indicated that the amount of reinforcement at the joints was insufficient.

The measured compression strain at failure was 4000 microstrain while the measured tension strain at failure was 6000 microstrain. Figure 4.6 shows close detail of the failure at the joints. The measured load-deflection relationship for Deck 1 is shown in Figure 4.7, and the measured load-strain relationship for Deck 1 is shown in Figure 4.8.

The measured deflection at 22 kips, which corresponds to HS20 truck load according to AASHTO specifications, was 0.6577 inch (span/73). The measured deflection at 26 kips, which corresponds to HS25 truck load according to AASHTO specifications, was 0.7739 inch (span/62). The measured deflection at 32 kips, which corresponds to HS30 truck load according to AASHTO specifications, was 0.9889 inch (span/48). The deflection at ultimate load of 34.4 kips was 1.1333 inch.

4.1.4 Behavior of Deck 2

Deck 2 has the same dimensions and configuration as Deck 1, except that the number of z-yarns at the joints were increased from six to twelve yarns. The deck sustained 14 cycles of loading with an increment of two kips before failure.
Failure of Deck 2 was due to crushing of the fibers in the compression surface as shown in Figure 4.9. The measured compression strain at failure was 6800 microstrain, while the tension side remained without damage, as shown in Figure 4.10, while the measured tension strain at failure was 9000 microstrain. This behavior reflected effective use of the material in comparison to Deck 1 and the adequate design of the number of yarns used at the connections. The measured load-deformation relationship for Deck 2 is shown in Figure 4.11, and the measured load-strain relationship for Deck 2 is shown in Figure 4.12.

The deflection at 22 kips, which corresponds to HS20 truck load according to AASHTO specifications, was 0.5593 inch (span/86). The deflection at 26 kips, which corresponds to HS25 truck load according to AASHTO specifications, was 0.6550 inch (span/73). The deflection at 32 kips, which corresponds to HS30 truck load according to AASHTO specifications, was 0.8213 inch (span/58). The deflection at ultimate load of 42.4 kips was 1.2736 inch.

4.1.5 Behavior of Deck 3

Deck 3 had a span of 84 inch, width of 18 inch, and height of 4.4 inch. All the joints have 12 z-yarns. The deck sustained 14 cycles of loading with an increment of two kips, before failure. Failure of deck 3 was due to crushing of the fibers in the compression zone. The measured compression strain at failure was 5800 microstrain, while the tension side remained elastic, with a measured tension strain of 8000 microstrain. The failure mode of Deck 3 is shown in Figures 4.13 and 4.14. The measured load-deformation relationship for Deck 3 is
shown in Figure 4.15, and the measured load-strain relationship for Deck 3 is shown in Figure 4.16.

The deflection at 22 kips, which corresponds to HS20 truck load according to AASHTO specifications, was 2.0159 inch (span/42). The deflection at 26 kips, which corresponds to HS25 truck load according to AASHTO specifications, was 2.3952 inch (span/35). The deflection at 32 kips, which corresponds to HS30 truck load according to AASHTO specifications, was 3.0518 inch (span/28). The deflection at ultimate load of 32.6 kips was 3.1391 inch.

4.2 Phase II: Effect of Type of Resin

To study the effect of the type of resin used to infuse the proposed bridge decks, two sandwich panels were fabricated and tested to compare the stiffness of the one panel infused with epoxy resin and another panel infused with vinyl ester resin.

The instrumentation used for both panels were similar to the instrumentation used to study the behavior of the three bridge decks represented in section 4.1. Three string potentiometers were placed at the center line of the panel along the Y-direction, and an average value was used to represent the midspan deflection. Two other potentiometers were placed at the two end supports, to measure the deflection of the neoprene pad supports.

Two BFLA 5.8.3L strain gages (Texas Measurements strain gages) were attached on each side of the panel, one in the X-direction, and one in the Y-direction. Both panels were tested in three point bending using a 220 MTS actuator with a clear span of 36 inch. The load was applied using displacement
controlled loading at a rate of 0.1 in/min, and loaded monotonically. The test setup for Panel 1 is shown in Figure 4.17; the test setup for Panel 2 is shown in Figure 4.18.

4.2.1 Behavior of Panel 1, Infused with Epoxy Resin

Panel 1 has a span of 36 inch, width of 10 inch, and depth of 2.2 inch, and was infused with epoxy resin. The panel was loaded monotonically and failure was due to buckling of the compression skin, accompanied by delamination of the balsa wood from the tension skin, as shown in Figure 4.19.

The measured failure load was 6.5 kips at a maximum midspan deflection of one inch, and the flexural rigidity EI was 6318 k.in². The measured compression and tension strains at failure were 8000 microstrain and Poisson’s ratio was found to be 0.1, while Poisson’s ratio in compression was found to be 0.2. The measured load-deformation relationship, is shown in Figure 4.20 and the measured load-strain diagram, is shown in Figure 4.21.

4.2.2 Behavior of Panel 2, Infused with Vinyl Ester Resin

Panel 2 has a span of 36 inch, width of 10 inch, and depth of 2.2 inch, and was infused with vinyl ester resin. The panel was loaded monotonically and failure occurred by delamination of the compression skin from the balsa wood, as shown in Figure 4.22.

The measured failure load was 5.7 kips at a maximum midspan deflection of one inch and the flexural rigidity EI was 5540 k.in². The measured compression and tension strain at failure were 6400 microstrain and Poisson’s ratio was found to
be 0.12, while Poisson’s ratio in compression was found to be 0.2. The measured load-deformation relationship is shown in Figure 4.23, and the measured load-strain relationship, is shown in Figure 4.24.

The behavior of the two panels indicated that using epoxy resin increased the stiffness by 14 percent in comparison to using vinyl ester resin. On the contrary, vinyl ester resin cost is one-half the cost of epoxy resin, more practical for bridge deck applications since it requires curing at room temperature while the epoxy resin requires elevated temperature for curing, for optimum properties. Also, the viscosity of vinyl ester is lower than the viscosity of epoxy which makes the infusion process quicker, and therefore, the fabrication time is quicker when infusing with vinyl ester resin.

4.3 Material Characteristics of 3-D GFRP Based on Coupon Tests

This section describes the different approaches used in this research to evaluate the material characteristics of the new 3-D GFRP material used in the construction of the 3-D GFRP bridge decks tested in this program.

4.3.1 Fiber Volume Fraction (ASTM D 3171-04)

The main source for strength and stiffness of FRP material is the fibers. The matrix has a minor contribution to the strength and stiffness. For example, FRP with fiber volume fraction of 60 percent would have a much higher strength and stiffness than those with fiber volume fraction of 40 percent. Therefore, it was imperative to determine the fiber volume fraction of the material used in the construction of the 3-D GFRP bridge deck tested in this program.
There are several methods which can be used to determine the fiber volume fraction, depending on the type of fibers and matrix used. For Glass/Epoxy, the most common method is an ignition test, where the volume of the glass fibers is measured, after burning of the epoxy.

The ignition test was conducted according to the ASTM standard D 3171-04. Sixteen specimens were cut (two specimens were grouped in one mug for accurate results); their mass and dimensions were reported. The volume of the specimens was determined using water-displacement method. The specimens were placed in ceramic mugs, as shown in Figures 4.25 and 4.26, and placed in a furnace. The furnace temperature was elevated to 400ºC in one hour, maintained at 400ºC for four hours and cooled to ambient temperature in one hour. The high temperature burned off the epoxy matrix leaving only glass fibers in the ceramic mugs. The mass of the fibers was determined based on the density of E-glass to obtain the volume of the fibers. The fiber volume fraction is the ratio of the volume of the fibers to the volume of the FRP. The average measured value of the sixteen specimens tested in this program was 47 percent. Detailed results of the fiber volume fraction for all the tested specimens are summarized in table 4.1.

**4.3.2 Tension Test (ASTM D 3039-00)**

The primary objective of the tension test is to evaluate the in-plane tensile properties of 3-D GFRP material produced from 3WEAVE® fabric. Five specimens were tested in the X-direction and additional three specimens were tested in the Y-direction. The test was conducted according to the ASTM
standard D 3039-00, and the load was applied using a 220 kips MTS universal testing machine.

Each specimen was approximately 12 inch long, one inch wide and 0.2 inch thick. Aluminum tabs were bonded to each end of the specimen to prevent premature failure at either ends, as shown in Figure 4.27 and tested in tension as shown in Figure 4.28.

Each specimen was attached to the grips of the MTS machine; the grips were closed providing a pressure of two psi on the Aluminum tabs. It should be noted that high pressure may weaken the FRP below the Aluminum tabs and result in premature failure in that region. The specimens were loaded monotonically using a loading rate of 0.001 in/sec. An extensometer was used to determine the longitudinal deformation using two inch gage length. Due to possible slippage during the loading process, the stroke reading from the testing machine was not used to determine the strain.

One strain gage (BFLA 5.8.3L from Texas Measurements) was attached in the X-direction and one strain gage was attached in the Y-direction to determine the longitudinal and the transverse strains, therefore, the Poisson’s ratio of the 3-D GFRP material.

Based on the measured deformation and the applied load, the stress-strain relationship was developed. The initial portion, up to 20 percent of the ultimate strain, was used to determine the elastic modulus of the 3-D GFRP. The average elastic modulus in the X-direction was found to be 3434 ksi, while the average tensile strength was found to be 74 ksi. The average elastic modulus in the Y-
direction was found to be 1424 ksi, while the average tensile strength was found to be 10.2 ksi. Poisson’s ratio was 0.12.

The stress-strain relationships of the X-direction and Y-direction are shown in Figures 4.29 and 4.30, respectively. The results of the all the coupons are shown in table 4.2. Table 4.3 shows statistical evaluation of the tension test results for the X-direction.

**4.3.3 Compression Test**

The compressive properties of 3-D GFRP were investigated using two different specimens configurations, according to ASTM D 3410/ D 3410 M – 03, and according to ASTM C 365.

**4.3.3.1 First Compression Test (ASTM D 3410–03)**

The test setup was similar to the setup of the tension test, except that the gage length between the aluminum tabs was one inch, to delay buckling of the 3-D GFRP skin. A total of five specimens were tested in the X-direction. One strain gage (BFLA 5.8.3L from Texas Measurements) was placed on each specimen in the longitudinal direction. An additional strain gage was placed in the transverse direction, in order to determine Poisson’s ratio in compression. The specimens were loaded monotonically using a 220 kips MTS machine, with a loading rate of 0.001 in/sec. Figure 4.31 shows the test setup.

The compression strength was not determined based on this test as buckling initiated the failure of all coupons, as shown in Figure 4.32. However, the elastic modulus in compression was determined from the initial portion of the stress-
strain relationship, and found to be 1720 ksi. Poisson’s ratio in compression was found to be 0.3. The compression test results are shown in table 4.4.

4.3.3.2 Second Compression Test (ASTM C365)

The objective of this test is to obtain the compressive strength of the 3-D GFRP; the elastic modulus in compression for the 3-D GFRP was obtained from the first compression test discussed above.

A total of eight specimens were tested. The specimens were cut from the bridge deck. Each specimen represents less than half of the cross-section of the deck. The specimens were tested with balsa cores between the skins as shown in Figure 4.25. The specimens were loaded monotonically to failure using the 220 kips MTS machine, with a rate of 0.001 in/sec.

The X-fibers were in the vertical direction between the loading plates with a depth of one inch, to avoid buckling of the skins. The dimensions of the 3-D GFRP alone were measured, and the dimensions of the balsa wood were measured. The compressive strength of the balsa was known from the manufacturer’s data sheet; therefore the calculation of the compressive strength of the 3-D GFRP was based on the following assumptions:

- The load carried by the 3-D GFRP = Ultimate load carried by the entire specimen – (compressive strength of the balsa x cross-sectional area of the balsa).

\[
\text{Compressive Strength of 3-D GFRP} = \frac{\text{The load carried by the 3-D GFRP}}{\text{Cross-sectional area of the 3-D GFRP}}
\]

The compressive strength of the 3-D GFRP was found to be 27.7 ksi.
Two strain gages were placed on one specimen, one on the top skin and one on
the bottom skin. The readings were not similar; due to the unsymmetrical area of
the 3-D GFRP in each of the two skins, caused due to the infusion process.
Figure 4.34 shows the typical failure of the compression specimens.
The test results are shown in table 4.5. Table 4.6 shows a statistical evaluation of
the compression test results (ASTM C 390).

4.3.4 Flexural Test

Flexural test was performed to evaluate the flexural strength and the elastic
modulus in flexure of the 3-D GFRP. Two different tests were conducted using
three point bending and four point bending tests. In three point bending the
maximum axial fiber stress is located immediately under the loading point, while
in the case of four point bending; the maximum axial fiber stress was uniformly
distributed between the loading noses. Also, in the case of the three point
bending, the midspan deflection was measured by the stroke of the machine,
while in the case of the four point bending the midspan deflection was measured
by a potentiometer. Since failure was expected under the loading points, the
deflection measured by the potentiometer was more accurate representation of
the midspan deflection. Therefore, the four point bending test results expected to
provide better representation of the flexural properties of 3-D GFRP material.
4.3.4.1 Three Point Bending Test (ASTM D 790-03)

The test was conducted according to the ASTM standard D790-03. Five specimens were tested in the X-direction and additional three specimens were tested in the Y-direction.

The dimensions of each specimen were approximately five inch long, one inch width, and 0.2 inch thickness. The simply supported span was three inch. The specimens were tested using a 220 kips MTS machine, and loaded monotonically with a rate of 0.001 in/sec. The test fixture and setup are shown in Figure 4.35.

Based on the measured deflection, D, the corresponding strain in the outer fibers, \( \varepsilon_f \), can be calculated as

\[
\varepsilon_f = \frac{6Dd}{L^2}
\]

Where:

\( d \) = Depth of the beam, inch
\( L \) = Support span, inch

Based on the measured load, P, the corresponding stress in the outer fiber, \( f_f \), can be calculated as:

\[
f_f = \frac{3PL}{2bd^2}
\]

Based on the above, the complete stress-strain relationship for all the tested specimens were developed; the initial portion up to 20 percent of the ultimate strain, was used to determine the elastic modulus of the 3-D GFRP material. The average ultimate strength in flexure in the X-direction was 43.6 ksi, while the
average elastic modulus in flexure was 1258 ksi. The average maximum stress in flexure in the Y-direction was 44.1 ksi, while the average elastic modulus in flexure was 2458 ksi. It was noticed that the modulus in the Y-direction is higher than the X-direction; each warp layer (X-fibers) had one filling yarn (Y-fibers) above it, and one filling yarn below it, repeated across the length of the fabric. Therefore, the overall depth of fibers in the Y-direction was higher than the overall depth of fibers in the X-direction. Therefore, the flexural modulus in the Y-direction was expected to be higher than in the X-direction. Typical failure of the three point bending coupons occurred under the point load, as shown in Figure 4.36.

A summary of all the three point bending test results are presented in table 4.7. Table 4.8 shows statistical evaluation of the three point bending test results for the X-direction. The stress-strain relationships for the X and Y directions are shown in Figure 4.37 and 4.38, respectively. The relationship is not perfectly linear. This behavior could be due to the stress concentration induced due to the applied single loads and could be particularly due to the relatively small magnitude of the measured strain.

4.3.4.2 Four Point Bending Test (ASTM D 6272-02)

The test was conducted according to the ASTM standard D 6272-02. A total of five specimens were tested in the X-direction, and additional three specimens were tested in the Y-direction.

The dimensions of each specimen were approximately five inch long, one inch width, and 0.2 inch thickness. The simply supported span was 3.25 inch loaded
at one half of support span. The specimens were tested using a 220 kips MTS machine, with a loading rate of 0.001 in/sec. A one inch potentiometer was placed at midspan to measure the maximum deflection. The test fixture and setup are shown in Figure 4.39.

Based on the measured deflection, $D$, the corresponding strain in the outer fibers, $\varepsilon_f$, can be calculated as

$$\varepsilon_f = \frac{4.36Dd}{L^2}$$

Based on the measured load, $P$, the corresponding stress in the outer fiber, $f_f$, can be calculated as:

$$f_f = \frac{3PL}{4bd^2}$$

Based on the above, the stress-strain relationship for all the tested specimens were developed; the initial portion up to 20 percent of the ultimate strain, was used to determine the elastic modulus of the 3-D GFRP material. Failure for all the coupons occurred under one of the loading points, as shown in Figure 4.40. The average maximum stress in flexure in the X-direction was 63 ksi, while the average elastic modulus in flexure was 2554 ksi. The average maximum stress in flexure in the Y-direction was 48 ksi, while the average elastic modulus in flexure was 5611 ksi.

The elastic modulus in flexure, in the Y-direction is again higher than in the X-direction due to the higher depth of fibers in the Y-direction as explained before. A summary of all the four point bending test results are presented in table 4.9. Table 4.10 shows statistical evaluation of the four point bending test results for
the X-direction. The stress-strain relationships for the X and Y directions are shown in Figure 4.41 and 4.42, respectively. The relationship is linear as seen in the Figures, which is typical for FRP materials.
Table 4.1 Fiber Volume Fraction Test Results (ASTM D 3171-04)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Volume of 3-D GFRP (ml, cm³)</th>
<th>Mass of Fibers after Ignition (grams)</th>
<th>Volume of Fibers (ml, cm³)</th>
<th>Fiber Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>23</td>
<td>47.76</td>
<td>18.23</td>
<td>0.46</td>
</tr>
<tr>
<td>1b</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>20</td>
<td>49.70</td>
<td>18.97</td>
<td>0.53</td>
</tr>
<tr>
<td>2b</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>16</td>
<td>45.94</td>
<td>17.53</td>
<td>0.55</td>
</tr>
<tr>
<td>3b</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>14</td>
<td>43.52</td>
<td>16.61</td>
<td>0.55</td>
</tr>
<tr>
<td>4b</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>15</td>
<td>41.40</td>
<td>15.83</td>
<td>0.55</td>
</tr>
<tr>
<td>5b</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>20</td>
<td>40.20</td>
<td>15.34</td>
<td>0.39</td>
</tr>
<tr>
<td>6b</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7a</td>
<td>26</td>
<td>49.25</td>
<td>18.80</td>
<td>0.38</td>
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<tr>
<td>7b</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8a</td>
<td>23</td>
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<td>0.38</td>
</tr>
<tr>
<td>8b</td>
<td>23</td>
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</tr>
</tbody>
</table>

Average Fiber Volume Fraction: 47%

Table 4.2 Tension Test Results (ASTM D 3039 – 00)

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Direction</th>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Tensile Strength (ksi)</th>
<th>Elastic Modulus (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>1.027</td>
<td>0.231</td>
<td>73.9</td>
<td>3446</td>
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<tr>
<td>2</td>
<td>X</td>
<td>1.025</td>
<td>0.218</td>
<td>65.9</td>
<td>2971</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>0.973</td>
<td>0.214</td>
<td>78.9</td>
<td>3506</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>1.036</td>
<td>0.258</td>
<td>77.0</td>
<td>3643</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>1.021</td>
<td>0.202</td>
<td>74.5</td>
<td>3604</td>
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</table>

Average 74

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Direction</th>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Tensile Strength (ksi)</th>
<th>Elastic Modulus (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td>0.959</td>
<td>0.238</td>
<td>10.4</td>
<td>1546</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>1.060</td>
<td>0.240</td>
<td>10.4</td>
<td>1260</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>0.986</td>
<td>0.235</td>
<td>09.8</td>
<td>1465</td>
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Average 10.2

Average 1424

Poisson’s Ratio 0.12
Table 4.3 Statistical Evaluation of Tensile Test Results (X-Direction)

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (X-Direction)</td>
<td>74</td>
<td>74.5</td>
<td>78.9</td>
<td>65.9</td>
<td>13</td>
<td>4.97</td>
<td>24.72</td>
</tr>
<tr>
<td>Elastic Modulus (X-Direction)</td>
<td>3434</td>
<td>3506</td>
<td>3643</td>
<td>2971</td>
<td>672</td>
<td>270.3</td>
<td>73069</td>
</tr>
</tbody>
</table>

Table 4.4 Elastic Modulus in Compression Results Obtained from First Compression Test (ASTM D 3410 – 03)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Elastic Modulus in Compression (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1789</td>
</tr>
<tr>
<td>2</td>
<td>1458</td>
</tr>
<tr>
<td>3</td>
<td>1620</td>
</tr>
<tr>
<td>4</td>
<td>1934</td>
</tr>
<tr>
<td>5</td>
<td>1801</td>
</tr>
</tbody>
</table>

Poisson’s Ratio in Compression 0.3 Average: 1720

Table 4.5 Compressive Strength Results Obtained from Second Compression Test (ASTM C 390)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Total Failure Load (kips)</th>
<th>Load Carried by Balsa Wood (kips)</th>
<th>Load Carried by 3-D GFRP (kips)</th>
<th>Cross-sectional Area of 3-D GFRP (in)</th>
<th>Compressive Strength of 3-D GFRP (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175.5</td>
<td>0.57</td>
<td>174.93</td>
<td>6.60</td>
<td>26.50</td>
</tr>
<tr>
<td>2</td>
<td>190.2</td>
<td>0.57</td>
<td>189.63</td>
<td>6.69</td>
<td>28.35</td>
</tr>
<tr>
<td>3</td>
<td>176.2</td>
<td>0.57</td>
<td>175.63</td>
<td>6.70</td>
<td>26.21</td>
</tr>
<tr>
<td>4</td>
<td>191.4</td>
<td>0.57</td>
<td>190.83</td>
<td>6.59</td>
<td>28.96</td>
</tr>
<tr>
<td>5</td>
<td>200.0</td>
<td>0.57</td>
<td>199.43</td>
<td>6.74</td>
<td>29.59</td>
</tr>
<tr>
<td>6</td>
<td>188.6</td>
<td>0.57</td>
<td>188.03</td>
<td>6.70</td>
<td>28.06</td>
</tr>
<tr>
<td>7</td>
<td>165.0</td>
<td>0.57</td>
<td>164.43</td>
<td>6.66</td>
<td>24.69</td>
</tr>
<tr>
<td>8</td>
<td>199.2</td>
<td>0.57</td>
<td>198.63</td>
<td>6.80</td>
<td>29.21</td>
</tr>
</tbody>
</table>

Average 27.7
Table 4.6 Statistical Evaluation of Compression Test Results (ASTM C 390)

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>27.70</td>
<td>28.20</td>
<td>29.60</td>
<td>24.70</td>
<td>4.90</td>
<td>1.72</td>
<td>2.97</td>
</tr>
</tbody>
</table>

Table 4.7 Three Point Bending Test Results (ASTM D790-03)

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Direction</th>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Maximum Stress in Flexure (ksi)</th>
<th>Elastic Modulus in Flexure (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>1.02</td>
<td>0.25</td>
<td>42.5</td>
<td>1341</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>1.02</td>
<td>0.22</td>
<td>42.0</td>
<td>1391</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>1.03</td>
<td>0.26</td>
<td>48.5</td>
<td>1471</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>1.02</td>
<td>0.23</td>
<td>45.0</td>
<td>1159</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>1.03</td>
<td>0.24</td>
<td>40.0</td>
<td>1065</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Maximum Stress in Flexure (ksi)</th>
<th>Elastic Modulus in Flexure (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average 43.6</td>
<td>Average 1285</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>1.05</td>
<td>0.21</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>1.08</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>1.07</td>
<td>0.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Maximum Stress in Flexure (ksi)</th>
<th>Elastic Modulus in Flexure (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average 44.1</td>
<td>Average 2458</td>
</tr>
</tbody>
</table>

Table 4.8 Statistical Evaluation of Three Point Bending Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Stress in Flexure (X-Direction)</td>
<td>43.6</td>
<td>42.5</td>
<td>48.5</td>
<td>50</td>
<td>8.5</td>
<td>3.27</td>
<td>10.67</td>
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<tr>
<td>Elastic Modulus in Flexure (X-Direction)</td>
<td>1285</td>
<td>1341</td>
<td>1471</td>
<td>1065</td>
<td>406</td>
<td>168.26</td>
<td>28311</td>
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### Table 4.9 Four Point Bending Test Results (ASTM D6372-02)

<table>
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<th>Coupon</th>
<th>Direction</th>
<th>Average Width (inch)</th>
<th>Average Thickness (inch)</th>
<th>Maximum Stress in Flexure (ksi)</th>
<th>Elastic Modulus in Flexure (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>1.120</td>
<td>0.237</td>
<td>65.7</td>
<td>2570</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>1.017</td>
<td>0.234</td>
<td>63.4</td>
<td>2535</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>1.028</td>
<td>0.230</td>
<td>58.3</td>
<td>2250</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>1.017</td>
<td>0.280</td>
<td>62</td>
<td>2843</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>1.120</td>
<td>0.247</td>
<td>65.7</td>
<td>2570</td>
</tr>
</tbody>
</table>

**Average**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>2554</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.10 Statistical Evaluation of Four Point Bending Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard Deviation</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (X-Direction)</td>
<td>63.0</td>
<td>63.4</td>
<td>65.7</td>
<td>58.3</td>
<td>7.4</td>
<td>3.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Elastic Modulus (X-Direction)</td>
<td>2554</td>
<td>2570</td>
<td>2843</td>
<td>2250</td>
<td>593</td>
<td>210</td>
<td>44202</td>
</tr>
</tbody>
</table>
Figure 4.1 Deck Cross Section

Figure 4.2 Test Setup for Deck 1
Figure 4.3 Test Setup for Deck 2

Figure 4.4 Test Setup for Deck 3

potentiometers to measure deflection of the neoprene pad supports

HSS to protect instrumentation when deck fails

4’ span

2 strain gages one in X direction and one in Y direction (additional 2 on tension side)
failure at the joints

Figure 4.5 Failure of Deck 1 at the Joints

Figure 4.6 Failure of Deck 1 at the Joints
Figure 4.7 Load Versus Midspan Deflection for Deck 1

Figure 4.8 Load Versus Strain for Deck 1
Figure 4.9 Failure of Deck 2

- Crushing of the top 3-D GFRP skin

Figure 4.10 Tension Side of Deck 2 after Failure

- No damage on the tension side at failure
Figure 4.11 Load Versus Midspan Deflection for Deck 2

Figure 4.12 Load Versus Strain for Deck 2
crushing of the top 3-D GFRP skin
Figure 4.15 Load Versus Midspan Deflection for Deck 3

Figure 4.16 Load Versus Strain for Deck 3
Figure 4.17 Test Setup for Panel 1

Figure 4.18 Test Setup for Panel 2
Figure 4.19 Failure of Panel 1

Figure 4.20 Load Versus Midspan Deflection for Panel 1

delamination of 3-D GFRP tension skin from the balsa wood
buckling of 3-D GFRP compression skin
Figure 4.21 Load Versus Strain for Panel 1

Figure 4.22 Failure of Panel 2
Figure 4.23 Load versus Midspan Deflection for Panel 2

Figure 4.24 Load Versus Strain for Panel 2
Figure 4.25 Fiber Volume Fraction Samples before Placement in the Furnace (ASTM D 3171-04)

Figure 4.26 Fiber Volume Fraction Samples after Burn off of Epoxy
Figure 4.27 Tension Coupons

Figure 4.28 Tension Test Setup (ASTM D3039 - 00)
Figure 4.29 Stress-Strain Relationship of All Coupons from Tension Test (X-Direction)

Figure 4.30 Stress Strain Relationship of All Coupons from Tension Test (Y-Direction)
Figure 4.31 Compression Test Setup (ASTM D 3410 – 03)

3-D GFRP skin with one inch gage length

Figure 4.32 Failure Initiated by Buckling of the 3-D GFRP Skin
Figure 4.33 Compression Test Setup (ASTM C 365)

Figure 4.34 Typical Failure of Compression Test Specimen
Figure 4.35 Three Point Bending Fixture and Test Setup (ASTM D 790-03)

Figure 4.36 Typical Failure of Three Point Bending Coupon under the Loading Point
Figure 4.37 Stress-Strain Relationship of All Coupons from Three Point Bending Test (X-Direction)

Figure 4.38 Stress-Strain Relationship of All Coupons from Three Point Bending Test (Y-Direction)
Figure 4.39 Four Point Bending Test Setup (ASTM D6372-02)

loading points at one half support span

3-D GFRP specimen

simple supports

one inch potentiometer to measure midspan deflection

Figure 4.40 Typical Failure of Four Point Bending Coupon under One of the Loading Points
Figure 4.41 Stress-Strain Relationship of All Coupons from Four Point Bending Test (X-Direction)

Figure 4.42 Stress-Strain Relationship of All Coupons from Four Point Bending Test (Y-Direction)
5. ANALYSIS AND DISCUSSION OF RESULTS

This chapter presents analysis of the measured experimental data obtained from the experimental investigation. Initially, an attempt was introduced to predict the behavior using the elementary sandwich theory. The second effort presented in this chapter include utilizing the measured overall deformation of the bridge decks, sandwich panels, and the coupon specimens to evaluate the material characteristics of the new innovative 3-D GFRP bridge decks.

5.1 Prediction of the Overall Behavior

The total deflection of the bridge deck is the result of the flexural and shear deformation under the applied load. To predict the deflection, the elementary sandwich theory was utilized since it includes both the flexural and shear deformation as discussed in the following section.

The total deflection, $\Delta_t$, due to the applied load, $P$, consists of the deflection due to flexure, $\Delta_b$, and the deflection due to shear, $\Delta_s$, as follows:

$$\Delta_t = \Delta_b + \Delta_s$$

Where:

$$\Delta_b = \frac{PL^3}{48EI}, \text{ and}$$

$$\Delta_s = \frac{PL}{4U}$$

$E$ is the elastic modulus, ksi

$I$ is the transformed inertia, in$^4$
U is the panel shear rigidity, \( \frac{G(d + c)^2b}{4c} \), kips

G is the shear modulus of the core material, ksi

For the tested bridge decks and panels; the width b was 18 inch and 10 inch, respectively. The transformed inertia for the bridge decks and the sandwich panels was 44.41 in\(^4\) and 2.23 in\(^4\), respectively. The cross-section of the bridge decks and the sandwich panels, with the dimensions discussed, are shown in Figures 5.1 and 5.2, respectively.

It should be mentioned that the bottom facing of the deck was relatively rough and not leveled since it was the top face during the infusion process. As a result, it was not practical to cut samples to evaluate the shear modulus, G, for the tested bridge decks. Due to the discussion issues, it was decided to determine only the two extreme bounds of the deflection rather than predicting the deflection.

The upper bound of the deflection, based on the flexural component, was evaluated by using the lower bound of the measured elastic modulus of the 3-D GFRP material of 1720 ksi, based on the test results from the compression coupon tests. The upper bound of the deflection, based on the shear component, was evaluated by using the published value of the shear modulus of the balsa core, of 14 ksi, therefore ignoring the contribution of the 3-D GFRP webs.

Accordingly, the upper bound of the total deflection, can be evaluated as the sum of the two upper bounds based on flexure and shear deformation. For the 48 inch span deck, the upper bound of the total deflection can be estimated in terms of the applied load as follows:
\[ \Delta_b = \frac{(P)(48)^3}{(48)(1720)(44.41)} = 0.030163 \text{ P} \]

\[ U = \frac{(14)(4.4 + 4)^2(16.4)}{(4)(4)} = 1012 \text{ k} \]

\[ \Delta_s = \frac{(P)(48)}{(4)(1012)} = 0.011858 \text{ P} \]

\[ \Delta_t = 0.030163 \text{ P} + 0.011858 \text{ P} = 0.042021 \text{ P} \]

The lower bound of deflection, based on the flexure component, was evaluated by using the higher elastic modulus, for the 3-D GFRP material of 3434 ksi, measured from the tension coupon tests. The lower bound of the deflection, based on the shear component, can be evaluated by using a shear modulus of 1533 ksi, which is based on the elastic formula of the shear modulus, \( G \), in terms of the elastic modulus, \( E \), and the Poisson’s ratio, \( \mu \), as:

\[ G = \frac{E}{2(1 + \mu)}. \]

It should be mentioned that the above equation for the shear modulus is for isotropic materials, and the 3-D GFRP used in this investigation is an orthotropic material, therefore, using the elastic modulus of the 3-D GFRP material would lead to over-estimate the shear modulus, used in this calculation. Therefore, the lower bound of the total deflection can be evaluated as follows:

\[ \Delta_b = \frac{(P)(48)^3}{(48)(3434)(44.41)} = 0.015108 \text{ P} \]

\[ U = \frac{(1533)(4.4 + 4)^2(1.6)}{(4)(4)} = 10,817 \text{ k} \]
\[ \Delta_s = \frac{(P)(48)}{(4)(10,817)} = 0.001109 \, P \]

\[ \Delta_t = 0.015108 \, P + 0.001109 \, P = 0.016217 \, P \]

The lower bound values, the upper bound values, and the measured deflection for all the decks, are given in tables 5.1 through 5.3. The comparison within the elastic range indicated that the deflection of the seven feet span deck is closer to the lower bound, than the deflection of the four feet span deck. This behavior could be due to the effect of the shear stresses which are larger for the case of the short span in comparison to the long span.

The same procedure was used to evaluate the tested sandwich Panel 1, which was infused by epoxy resin and does not have the webs used for the bridge decks. In this case, since the panel has only balsa wood as the core material, there is one limit for the shear deformation component, while there remain two bounds for the flexural deformation component that can be evaluated using the large value of \( E \), of 3434 ksi, measured from the tension coupons, and the lower value of \( E \), of 1720 ksi, measured from the compression coupons.

It was noticed that the measured deflection is very close to the lower bound values, which were based on the large value of \( E \) of 3434 ksi. The lower bound values, the higher bound values, and the measured deflection of Panel 1 are given in table 5.4.

**5.2 Evaluation of the Elastic Modulus of 3-D GFRP**

The following sections utilize the experimental results to provide a range for the elastic modulus, which can be used to predict deflection of the 3-D GFRP bridge
decks. This analysis includes, the overall behavior of the bridge decks, the overall behavior of the sandwich panels, the overall behavior of the flexural coupon specimens, the measured strains of the decks and panels, and the principal of the rule of mixtures.

5.2.1 Using the Overall Behavior of the Decks

This section aims to utilize the experimental results to evaluate the elastic modulus in flexure based on the measured deflection of the three bridge decks. For each bridge deck, three limits are used to evaluate the elastic modulus in flexure. The upper limit can be evaluated by considering the shear deflection component due to the contribution of the balsa wood. This limit provides a low value for the shear rigidity of the deck and therefore results in a high value for the shear deflection component. Therefore, for a given measured value of the total deflection, this limit results in a low value for the flexure deflection component and therefore, an upper limit for $E$. For the 48 inch span deck, the upper limit can be evaluated, in terms of the applied load, $P$, and the total deflection, $\Delta_t$, as follows:

$$\Delta_t = \Delta_b + \Delta_s$$

$$\Delta_t = \frac{PL^3}{48EI} + \frac{PL}{4U}$$

$$U = \frac{(14)(8.4)^2(16.4)}{(4)(4)} = 1012 \text{ k}$$

$$\Delta_t = \frac{51.88P}{E} + 0.0118 P$$
\[ E = \frac{51.88P}{\Delta_t - 0.0118P} \]

All the limits were evaluated at different load values from 20 to 30 kips. This range was selected to be within the elastic region and away from the seating region. The upper limit of \( E \), for Deck 1 ranged between 2834 to 2940 ksi, for Deck 2 was from 3806 to 3888 ksi, and for Deck 3 was from 3817 to 3942 ksi.

The intermediate limit, can be evaluated by using the shear deflection component due to the 3-D GFRP. In this case, the corresponding shear rigidity of the deck is much higher than in the first case and therefore provides a low value for the shear contribution to the deflection. Therefore, for a given measured value of the total deflection, this limit results in an intermediate value for the flexure deflection component and therefore, an intermediate limit for \( E \). For the 48 inch span deck, the intermediate limit can be evaluated, in terms of the applied load, and the total deflection, as follows:

\[ \Delta_t = \frac{PL^3}{48EI} + \frac{PL}{4U} \]

\[ G = \frac{E}{2(1 + 0.12)} = \frac{E}{2.24} \]

\[ U = 3.15 \, E \]

\[ \Delta_t = \frac{PL^3}{48EI} + \frac{PL}{(4)(3.15E)} \]

\[ \Delta_t = \frac{51.88P}{E} + \frac{3.8095P}{E} = \frac{55.69P}{E} \]

\[ E = \frac{55.69P}{\Delta_t} \]
The intermediate limit of $E$, for Deck 1 ranged from 1846 to 1888 ksi, for Deck 2 was from 2185 to 2210 ksi, and for Deck 3 was from 3042 to 3119 ksi. The lower limit can be evaluated by using the shear deflection component due to both the 3-D GFRP and the balsa wood. In this case an approximate value for the shear modulus of the core was used which was calculated proportional to the width of each material. This limit provides the highest shear rigidity, which corresponds to the lowest shear deflection. Therefore, for a given measured value of the total deflection, this limit results in the highest value for the flexure deflection component and therefore, a lower limit for $E$. For the 48 inch span deck, the lower limit can be evaluated, in terms of the applied load, and the total deflection, as follows:

$$G = G_{3D\ GFRP} \times \frac{1.6}{18} + G_{balsa} \times \frac{16.4}{18}$$

$$G = 1533 \times \frac{1.6}{18} + 14 \times \frac{16.4}{18} = 149 \text{ ksi}$$

$$\Delta_t = \frac{PL^3}{48EI} + \frac{PL}{4U}$$

$$U = \frac{(149)(8.4^2)(18)}{(4)(4)} = 11,828 \text{ kips}$$

$$\Delta_t = \frac{51.88P}{E} + 0.00101P$$

$$E = \frac{51.88P}{\Delta_t - 0.00101P}$$

The lower limit of $E$, for Deck 1 ranged from 1780 to 1821 ksi, for Deck 2 was from 2120 to 2145 ksi, and for Deck 3 was from 3028 to 3106 ksi. It was noticed
that the intermediate limits and the lower limits are very close since the
collection of the balsa wood to the stiffness is negligible.
The limits for $E$ based on the measured deflection for all three decks are shown
in Figures 5.3 through 5.5.
Based on the analysis of this section, the lower limit of $E$ is believed to provide
better approximation, since it accounts for the 3-D GFRP webs and the balsa
wood.

5.2.2 Using the Overall Behavior of the Sandwich Panels
The sandwich panels tested for the resin study were also utilized to evaluate the
elastic modulus in flexure. In this case elementary sandwich theory can be
directly applied using one limit for each panel. In this case, the shear modulus for
the core material was 14 ksi, which is the shear modulus of the balsa wood. For
the span of 36 inch, the elastic modulus can be evaluated in terms of the applied
load, and the total deflection, as follows:

$$U = \frac{(14)(4.2)^2(10)}{(4)(2)} = 309 \text{ k}$$

$$\Delta_t = \frac{PL^3}{48EI} + \frac{PL}{4U}$$

$$\Delta_t = \frac{(P)(36)^3}{(48)(E)(2.2326)} + \frac{(P)(36)}{(4)(309)}$$

$$\Delta_t = \frac{435P}{E} + 0.0291 \text{ P}$$

$$E = \frac{435P}{\Delta_t - 0.0291P}$$
The limit of E was evaluated at different load values from 2 to 4.5 kips. The limit for Panel 1, which was infused with epoxy resin, ranged from 3471 to 3700 ksi. The limit for Panel 2, which was infused with vinyl ester resin, ranged from 3221 to 3390 ksi. The limits of E based on the measured deflection of Panels 1 and 2 are shown in Figure 5.6.

Therefore, based on the analysis of this section, an approximate limit of E, have been provided, which could be used to predict deflection of the 3-D GFRP sandwich panels, infused with epoxy resin or infused with vinyl ester resin.

**5.2.3 Using the Overall Behavior of the Flexural Specimens**

The elastic modulus in flexure was evaluated based on the overall deflection of the four point bending coupons. The test configuration is shown in Figure 5.7. For a clear span, L, of 3.25 inch, the elastic modulus can be evaluated based on the midspan deflection, $\Delta t$, in terms of the applied load, P, where b is the width of the coupon, and d is the depth of the coupon, as follows:

$$\Delta t = \frac{(P/2)(a)(3L^2 - 4a^2)}{24EI}$$

$$\Delta t = \frac{(P/2)(L/4)(11L^2 / 4)}{24EI}$$

$$\Delta t = \frac{11PL^3}{768EI}$$

$$E = \frac{5.9P}{\Delta_t bd^3}$$

The limit of E was evaluated at different load values from 0.5 to 1.25 kips and was found to be from 1929 to 2174 ksi. The low values for E based on the four
point bending coupons, could be due to shear stresses induced in the coupons
due to the short span of 3.25 inch. The limit for E based on the flexural
specimens is shown in Figure 5.8.

**5.2.4 Using the Measured Strains of the Decks and the Panels**

This section aims to evaluate the elastic modulus based on the measured
tension and compression strains, for the tested decks and panels.
The maximum strain in compression and the maximum strain in tension were
measured for all three decks, and the two panels. Based on the strain
distribution, the location of the neutral axis was determined at different load
points, for the given section. The elastic modulus, \( E \), can be evaluated as:
\[
E = \frac{M Y_{bottom}}{I \varepsilon_{tension}}, \quad \text{or} \quad E = \frac{M Y_{top}}{I \varepsilon_{compression}}
\]

Where:

- \( M \) is the moment due to the concentrated load, \( P \), at midspan.
- \( Y_{bottom} \) is the distance from the neutral axis to the bottom tension fiber; and
- \( Y_{top} \) is the distance from the neutral axis to the top compression fiber.

Since, \( M/I \) is constant at a given load point, therefore, \( Y_{bottom}/\varepsilon_{tension} = Y_{top}/\varepsilon_{compression} \) from similar
triangles of the strain diagram.

Therefore, based on the assumption of linear strain profile, the elastic modulus in
tension is the same for the compression.

The elastic modulus, \( E \), was evaluated at different load points, within the range of
20 to 30 kips, for the decks, and from 2 to 4.5 kips for the panels. The range of \( E \)
using this approach ranged from 3300 to 4900 ksi. It was noticed that these
values are higher than the ranges of $E$ based on the other discussed approaches. This indicates that the assumption of linear strain distribution is not strictly applicable in the case of 3-D GFRP bridge decks tested in this program. The load versus elastic modulus, based on the measured tension and compression strains, for the three decks, and the two panels are shown in Figures 5.9 and 5.10, respectively.

### 5.2.5 Principal of the Rule of Mixtures

The rule of mixtures provides a reasonable approximation of the elastic modulus in tension, to uniaxial FRP. Since the material used in this program consists of fibers in three dimensions, the elastic modulus of the fibers, $E_f$, is reduced by 30 percent, which is proportional to the percentage of the fibers in the X-direction of 70 percent in comparison to the total amount of fibers.

The elastic modulus in the X-direction in terms of the fiber volume fraction, $V_f$, the elastic modulus of the fibers, $E_f$, and the elastic modulus of the matrix, $E_m$, can be expressed as follows:

$$E = V_f E_f + (1-V_f) E_m$$

For the 3-D GFRP tested in this program, $V_f$ is 0.47 based on the experimental results; and $E_f$ is 10,500 ksi, and $E_m$ is 465 ksi, based on the manufacturer’s data sheet.

Therefore, $E = (0.47 \times 10,500 \times 0.7) + (0.53 \times 465) = 3700$ ksi

In the previous chapter, the elastic modulus was evaluated based on coupon tests and found to be 1720 ksi, based on the compression test; 2554 ksi based on the four point flexure test; and 3434 ksi based on the tension test.
This chapter presented an evaluation of the elastic modulus based on measured experimental values for the overall 3-D GFRP bridge decks and sandwich panels, with different spans. The analysis from both categories provides consistent ranges for the elastic modulus that can be applied in any future investigation on the 3-D GFRP material.

The analysis indicates that a conservative value of 2800 ksi can be used for the elastic modulus of the new 3-D GFRP bridge decks with the specific design orientation of the fibers. This value also accounts for the balsa wood and the variation of the material properties of the top and bottom skins of the deck, due to the infusion process presented in this thesis. It should be mentioned that the recommended value of $E$ is approximately 70 percent of the value based on the principal of the rule of mixtures, due to the issues discussed above.
### Table 5.1 Deflection Evaluation for Deck 1

<table>
<thead>
<tr>
<th>Load</th>
<th>Lower Bound (inch)</th>
<th>Upper Bound (inch)</th>
<th>Measured Value (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS 20 (22 kips)</td>
<td>0.3579</td>
<td>0.9277</td>
<td>0.6577 (span/73)</td>
</tr>
<tr>
<td>HS 25 (26 kips)</td>
<td>0.4244</td>
<td>1.0998</td>
<td>0.7739 (span/62)</td>
</tr>
<tr>
<td>HS 30 (32 kips)</td>
<td>0.5198</td>
<td>1.3470</td>
<td>0.9889 (span/48)</td>
</tr>
</tbody>
</table>

### Table 5.2 Deflection Evaluation for Deck 2

<table>
<thead>
<tr>
<th>Load</th>
<th>Lower Bound (inch)</th>
<th>Upper Bound (inch)</th>
<th>Measured Value (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS 20 (22 kips)</td>
<td>0.3597</td>
<td>0.9280</td>
<td>0.5593 (span/86)</td>
</tr>
<tr>
<td>HS 25 (26 kips)</td>
<td>0.4233</td>
<td>1.0922</td>
<td>0.6550 (span/73)</td>
</tr>
<tr>
<td>HS 30 (32 kips)</td>
<td>0.5235</td>
<td>1.3507</td>
<td>0.8213 (span/58)</td>
</tr>
</tbody>
</table>

### Table 5.3 Deflection Evaluation for Deck 3

<table>
<thead>
<tr>
<th>Load</th>
<th>Lower Bound (inch)</th>
<th>Upper Bound (inch)</th>
<th>Measured Value (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS 20 (22 kips)</td>
<td>1.8256</td>
<td>4.0161</td>
<td>2.0159 (span/42)</td>
</tr>
<tr>
<td>HS 25 (26 kips)</td>
<td>2.1561</td>
<td>4.7436</td>
<td>2.3952 (span/35)</td>
</tr>
<tr>
<td>HS 30 (32 kips)</td>
<td>2.6538</td>
<td>5.8385</td>
<td>3.0518 (span/28)</td>
</tr>
</tbody>
</table>

### Table 5.4 Deflection Evaluation for Panel 1

<table>
<thead>
<tr>
<th>Load (kips)</th>
<th>Lower Bound (inch)</th>
<th>Upper Bound (inch)</th>
<th>Measured Value (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.4678</td>
<td>0.8252</td>
<td>0.4495</td>
</tr>
<tr>
<td>4</td>
<td>0.6237</td>
<td>1.1003</td>
<td>0.6138</td>
</tr>
<tr>
<td>5</td>
<td>0.7798</td>
<td>1.3753</td>
<td>0.7922</td>
</tr>
</tbody>
</table>
Figure 5.1 Cross-Section of the Bridge Decks

d = 4.4"
b = 18"
c = 4"

4.65"
0.4"

Figure 5.2 Cross-Section of the Sandwich Panels

d = 2.2"
b = 10"
c = 2"
Figure 5.3 Limits for E Based on Measured Deflection of Deck 1

Figure 5.4 Limits for E Based on Measured Deflection of Deck 2
Figure 5.5 Limits for E Based on Measured Deflection of Deck 3

Figure 5.6 Limit for E Based on Measured Deflection of Panel 1 and Panel 2
Figure 5.7 Test Configuration for the Flexural Test

Midspan Deflection, \( \Delta_t = \frac{(P/2)(a)(3L^2 - 4a^2)}{24EI} \)

Figure 5.8 Limit for E Based on Measured Deflection of the Four Point Bending Coupon Tests
Figure 5.9 Load Versus Elastic Modulus Based on Measured Tension and Compression Strains for the Three Decks

Figure 5.10 Load Versus Elastic Modulus Based on Measured Tension and Compression Strains for Panel 1 and Panel 2
6. SUMMARY AND CONCLUSIONS

6.1 General

A comprehensive experimental study was conducted to investigate the use of 3-D GFRP material to produce new and innovative bridge decks for highway bridges. The research focused on the most effective concept that can be used and included thorough investigation to determine the material characteristics. The limited test results of the overall behavior of the tested decks indicated a very promising potential for the use of this material for future generation of bridge decks.

The main advantage in using the 3-D weaving technology is the elimination of the typical delamination observed for pultruded GFRP decks currently in use.

6.1.1 Overall Behavior

Three bridge decks were tested in this program, the first two were four feet span, and the third one was seven feet span. The first two decks had different amount of fiber reinforcement at the joints; to study the influence of this parameter on the overall behavior. The two ranges of the spans were used to determine the effect of the shear deformation on the overall behavior. The seven feet span bridge deck was used to study the typical behavior of these types of decks in real field applications.

Test results has shown that the 3-D GFRP bridge decks have sufficient capacity; however, exhibited larger deflections than that specified by AASHTO specifications, since the selected depth was restricted to the capacity of the
textile machine used. It is obvious that this behavior can be simply overcome by increasing the overall depth of the deck and/or using thicker fabrics. The behavior can be significantly enhanced by the use of concrete layer in the compression zone to act in composite action with the GFRP bridge deck. This concept was the main topic of a companion thesis conducted parallel to this investigation (Johnson, 2006).

6.1.2 Effect of Type of Resin

Two sandwich panels were fabricated and tested in this program. One panel was infused by epoxy resin, and the other panel was infused by vinyl ester resin. The results show that the panel infused by epoxy resin exhibited 14 percent higher stiffness than the panel infused by vinyl ester resin. However, it should be noticed that epoxy resin required elevated post-cure temperature for optimum results, while vinyl ester is typically cured at room temperature. The overall cost of epoxy resin system is approximately double the overall cost of the vinyl ester resin system. Since the epoxy resin has higher viscosity than vinyl ester resin, the production time is also much larger. Based on this limited results, and taking in to account the superior durability of the epoxy, it is recommended to use the epoxy resin for infusion of these type of bridges.

6.1.3 Strength of the 3-D GFRP Material

The experimental program included testing of specimens cut from the tested bridge decks and tested in tension, compression and flexure. The tensile and
compressive properties of 3-D GFRP material were determined, as well as the flexural properties of 3-D GFRP material. In general, the material exhibited high tensile strength of an average value of 74 ksi in the X-direction, and a compressive strength of an average value of 27 ksi. The overall measured flexural strength ranges within the measured tensile and compressive strengths using the coupon specimens. The measured elastic modulus was relatively low in comparison to concrete and steel bridge decks.

6.1.4 Elastic Modulus of 3-D GFRP

The elastic modulus of the 3-D GFRP was evaluated analytically using the overall behavior of the decks, the flexural coupon specimens, and the principal of the rule of mixtures. Based on the measured deflection, lower, intermediate, and upper limits are established for each tested deck and the sandwich panel tested in this program. In summary, the study concluded that the lower and upper limits of the elastic modulus are 1800 ksi and 3900 ksi, respectively. Therefore, an average value of 2800 ksi, can be used for design purposes.

6.2 Future Work

The bridge decks used in this investigation was limited by the size of the existing equipment at 3TEX, Incorporated, to produce a maximum width of 20 inch. Therefore, it is highly recommended to modify the equipment to produce typical bridge decks with at least six ft width. In this case, future study should investigate the effective width for the truck wheel distribution and their effect on the overall
flexural behavior. The other limitation of the overall depth of four inch should also be increased to reduce the deflection to meet AASHTO specifications.

To eliminate possible pre-mature failure of the deck at the joint location, observed in Deck 1, it is proposed to increase the width of the joint length. The number of the webs can also be increased by using double webs which can be achieved by cutting in between the joints, as shown in Figure 6.1.

Future work should also include comprehensive finite elements simulation of the new deck to optimize the various parameters which can significantly enhance the behavior. These parameters are the overall dimensions, web thickness, number of webs, and the thickness of the top and bottom layers.

Future work may consider further study of the type of resin since it greatly affects the overall cost of the bridge deck.

Behavior of the deck should also be investigated under fatigue loading conditions.
Figure 6.1 Proposed Third Generation Cross-Section for the 3-D GFRP Bridge Deck
7. REFERENCES


44. ASTM C 393 – 00 Standard Test for Flexural Properties of Sandwich Constructions.


8. APPENDICES
Appendix A (Hybon 2022 E-Glass Fibers)

TECHNICAL DATA SHEET

Hybon ® 2022 Roving

Application Hybon® 2022 Roving is a single end roving for filament winding and weaving/knitting applications and is made of electrical (E) glass fiber. This roving is compatible with polyester, vinyl ester, epoxy, and phenolic resin systems.

Hybon® 2022 Roving is designed for applications that require maximum wet-out and wet-out consistency, together with good abrasion resistance and processing characteristics. It is suitable for applications such as piping in oil-field CO₂ gathering systems and pressure cylders.

• Provides strand hardness without sacrificing rapid and complete wet-out

• Excellent payout and package transfer

• Low resin demand during processing Excellent package transfer efficiency

through the use of an outer adhesive filmSupported by PPG’s e resources

PACKAGING & PALLETIZING DATA

Packaging Option 1:
• Yields: 103, 206, 413 & 827
• 48 packages/pallet
• Pallet weight: 980 kg
• Package weight: 20.4 kg

Packaging Option 2:
• Yields: 218, 225, 250, 288, 330, 450, 675, 1200 & 1800
• 60 packages/pallet
• Pallet Weight: 1,225 kg
• Package Weight: 20.4 kg

Caution: To avoid the possibility of potential injury, maintain column stability by limiting pallet stacking to two high as noted on individual shipping container.

Storage: These products should be stored at room temperature and at a relative humidity of 65% +/- 10%. To avoid problems with humidity or static electricity, the glass product should be conditioned in the working area prior to use.
### PRODUCT DESCRIPTION

<table>
<thead>
<tr>
<th>Type of Fiber</th>
<th>E-Glass (ASTM D578-98, paragraph 4.2.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Sizing</td>
<td>Silane</td>
</tr>
<tr>
<td>Roving Yields, nominal ± 7% (yd/lb)</td>
<td>103 206 218 225 250 288 330 413 450 675 827 1200 1800</td>
</tr>
<tr>
<td>Tex, nominal ± 7% (g/km)</td>
<td>4800 2400 2275 2200 1985 1722 1500 1200 1100 735 600 413 276</td>
</tr>
<tr>
<td>Fiber Diameter, nominal</td>
<td>T MN MN T M LM Q MN MN K K OR MN K OR MN K</td>
</tr>
<tr>
<td>Micrometers, μm</td>
<td>24 17 17 24 16 15 20 17 17 13 13 OR 17 13 OR 17 13</td>
</tr>
<tr>
<td>Percent of Sizing (by wt. of glass)</td>
<td>.55 .55 .55 .55 .55 .55 .55 .55 .55 .55 .55 .55 .55 .55</td>
</tr>
</tbody>
</table>

1-800-613-0155fgcustservice@ppg.com www.ppgfiberglass.com

**Specific Gravity** (bare fiber)
2.59 g/cm³

For commercial fiber glass products with sizing (binder), specific gravity and density are reduced by 0.02 g/cm³ and 0.0007 lb/in³ respectively for each one percent by weight of sizing application.

**Density** (bulk), 0.094 lb/in³
2.63 g/cm³

**Tensile Strength, @ 50% Relative Humidity 72 °F**
200 - 300 x 10³ psi
1380 - 2070 MPa

**Modulus of Elasticity**
10.5 x 10⁶ psi
72.45 Gpa

**Elastic Recovery**
100%

**Elongation** at break
3 - 4%

**Poisson’s Ratio**
0.22
**Linear Coeff. of Thermal Expansion** (25 - 300 °C)
2.8 - 3.3 x 10^-6 in/(in °F)
5.0 - 6.0 x 10^-6 cm/(cm °C)

**Thermal Conductivity** (bulk)
0.6 - 0.7 btu/(hr-ft °F) @ 72 °F
0.0025 - 0.003 cal/(sec-cm °C) @ 22 °C

**Specific Heat** (bulk)
0.197 btu/(lb °F) @ 72 °F
0.197 cal/(g °C) @ 22 °C

**Softening Point**
1540 °F
838 °C

**Dielectric Constant**
6.7 @ 106 Hz & 72 °F (22 °C)

**Index of Refraction @ 550 nanometers**
1.559

**Ultraviolet transmission**
opaque

**Hardness** (moh scale) (bulk)
6.5
Appendix B (JEFFCO Epoxy System for Infusion 1401-21/4101-21)

JEFFCO 1401-21/4101-21

Epoxy System for Infusion

DESCRIPTION: Multifunctional epoxy and cycloaliphatic-amine blend hardener for high performance composite parts. Two curing agents (4101-21 fast and 4101-21 slow) provide a complete range of working times from 40 minutes to 6 hours, and by blending the curing agents, any point in between. 1401-21 with 4101-21 provides for ample pot life with fast cure development at standard molding temperatures. Jeffco 1401-21 provides good thermal resistance, excellent fatigue and inter-laminar shear strength with rapid wetting of E-glass fiber reinforcements. Jeffco 1401-21 Epoxy Resin is formulated for highly increased E-glass fiber compatibility. Low toxicity, low odor system. No VOC’s, 100% solids.

SUGGESTED USES: Resin infused composite rotor blades, other large fiberglass reinforced structures.

SYSTEM LIQUID PROPERTIES:

<table>
<thead>
<tr>
<th></th>
<th>1401-21 Resin, 77°F</th>
<th>4101-21 Slow Hardener, 77°F</th>
<th>4101-21 Fast Hardener</th>
<th>Mix Ratio, Resin to Hardener</th>
<th>Weight Per Gallon, 1401-21 Resin</th>
<th>Weight Per Gallon, 4101-21 Hardener</th>
<th>Weight per Gallon, Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>750-900 cps</td>
<td>20 cps</td>
<td>50 cps</td>
<td>100:30 by weight</td>
<td>9.5 - 9.6 lbs.</td>
<td>7.9-8.1 lbs.</td>
<td>9.2 lbs</td>
</tr>
<tr>
<td>Mixed Viscosity, 77°F</td>
<td>160 cps (slow)</td>
<td>240 cps (fast)</td>
<td>240 cps (fast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Viscosity, 100°F</td>
<td>90 cps (slow)</td>
<td>130 cps (fast)</td>
<td>130 cps (fast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GEL TIME RECIPE TABLE: Jeffco 1401-21 Resin, 100 parts, Jeffco 4101-21 as specified, 30 parts:

<table>
<thead>
<tr>
<th>Gel Time, 150 grams @ 77 °F</th>
<th>Percent of 4101-21 Slow</th>
<th>Percent of 4101-21 Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>360 minutes</td>
<td>100% (30PHR)</td>
<td>-</td>
</tr>
<tr>
<td>160 minutes</td>
<td>90% (27PHR)</td>
<td>10% (3 PHR)</td>
</tr>
<tr>
<td>100 minutes</td>
<td>75% (23 PHR)</td>
<td>25% (7 PHR)</td>
</tr>
<tr>
<td>70 minutes</td>
<td>60% (18PHR)</td>
<td>40% (12 PHR)</td>
</tr>
<tr>
<td>40 minutes</td>
<td>-</td>
<td>100% (30 PHR)</td>
</tr>
</tbody>
</table>

RESIN INFUSION BASICS: Condition epoxy resin and hardener to between 24°C and 38°C (75°F to 100°F) to ensure proper mixed viscosity. Introduce mixed material into part to be infused keeping mold temperature between 35°C and 40°C (95°F to 104°F). Place or position injection ports to introduce material as needed to ensure injection within two hours. Under moderate vacuum, inject material for up to 120 minutes at the above temperature parameters. Once injection is complete, increase mold temperature to
between 50°C and 65°C (122°F to 149°F). Hold at this temperature for between 4 and 6 hours. Cure temperatures may be from 50°C to 85°C to accomplish maximum HDT. Optimum cure time(s) versus temperature(s) will depend on parameters such as part thickness or size.

REINFORCEMENT TYPES: Jeffco 1401-21 Epoxy Resin is specially formulated for highly increased compatibility with E-glass reinforcements. For carbon fiber laminates, Jeffco 1401-14 Epoxy Resin should be used. When using E-glass / carbon fiber hybrid fabrics or reinforcements, Jeffco 1401-16 Epoxy Resin is recommended. All three Epoxy Resins are compatible and recommended with Jeffco 4101 series Epoxy Hardener(s). Please refer to the specific Jeffco Epoxy Resin product bulletin for more information.

ADVANTAGES OF JEFFCO 1401-21 EPOXY RESIN: As discussed previously, Jeffco 1401-21 Epoxy Resin is formulated to improve the intimate bond between the epoxy resin and E-glass fiber reinforcements. This formulation technique results in increased physical properties as follows:

♦ Fiber Pull-Out Strength
♦ Tensile Strength and Modulus
♦ Flexural Strength and Modulus
♦ Compressive Strength
♦ Impact Resistance
♦ Inter-Laminar Shear Strength

Of equal, if not greater significance is the retention of the above properties after exposure to heat, cycle fatigue, water, expected adverse environmental reagents such as salt spray, acid rain, etc. The formulation of Jeffco 1401-21 Epoxy Resin results in minimal degradation of the cured composite’s physical properties as compared to epoxy resin systems not containing the proprietary formulation constituents of Jeffco 1401-21 Epoxy Resin. Similar results with carbon reinforced composites are obtained with Jeffco 1401-14 Epoxy Resin and carbon / E-glass hybrids with Jeffco 1401-16 Epoxy Resin.

The benefit to the composite fabricator is obvious and clear: Increased product life and confidence!

CURED PHYSICAL PROPERTIES OF COMPOSITE: A-260 unidirectional E-glass (epoxy compatible rovings) with Jeffco 1401-21 Epoxy Resin and 4101-21 Epoxy Hardener (70:30 glass to resin ratio). Cure schedule – 2 hours at 35ºC (infusion) / 4 hours at 65ºC (basic cure) / 2 hours at 85ºC (final cure).

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>83,000 psi</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>5,250,000 psi</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>90º Tensile Strength</td>
<td>6.05 ksi</td>
<td>ASTM D 3039</td>
</tr>
<tr>
<td>In-Plane Shear Strength</td>
<td>9.14 ksi</td>
<td>ASTM D 3518</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>86,000 psi</td>
<td>ASTM D 790</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>2,490,000 psi</td>
<td>ASTM D 790</td>
</tr>
<tr>
<td>Izod Impact</td>
<td>44.5 ft/lb/in</td>
<td>ASTM D 256-A</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>0.09%</td>
<td>ASTM D 570</td>
</tr>
<tr>
<td>Barcol Hardness</td>
<td>64</td>
<td>Jeffco Products</td>
</tr>
</tbody>
</table>

CURED PHYSICAL PROPERTIES OF NEAT RESIN: Jeffco 1401-21 Epoxy Resin, 100 parts, Jeffco 4101-21 Epoxy Hardener, 30 parts. 2 hours at 35ºC (infusion) + 4 hours at 60ºC (basic cure).

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tg (DSC)</td>
<td>194ºF (90ºC)</td>
<td>IPC-TM-650, 2.4.25</td>
</tr>
<tr>
<td>Shore D Hardness</td>
<td>90D</td>
<td>Jeffco Products</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>10.30 Ksi</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>Ultimate Elongation</td>
<td>7.4 -7.5%</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>465 Ksi</td>
<td>ASTM D 638</td>
</tr>
<tr>
<td>Ultimate Compressive Strength</td>
<td>14,500 psi</td>
<td>Sandia Labs Method</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>18.65 Ksi</td>
<td>ASTM D 790</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>430 Ksi</td>
<td>ASTM D 790</td>
</tr>
</tbody>
</table>
Supplied in 5 Gallon Pails, 55 Gallon Drums, 250 Gal IBC’s, Combination Bulk Tanker (4,000 Gals). Curing agent(s) may be ordered as premixed blends in larger quantities.
Appendix C (AME-6000-35)

AME™6000-35 INF
Marine Infusion Resin
March 2005

AME 6000-35 INF is a high performance, low VOC, 100% epoxy vinyl ester premium marine infusion resin. This resin is prepromoted and formulated for resin transfer molding and vacuum infusion processing.

- Excellent blister resistance
- Fast wet-out of glass fibers
- User friendly processing
- Less than 35% styrene
- Good surface profile
- Excellent mechanical properties

Recommended Product Applications

AME 6000-35 INF resin is recommended for marine applications that require low HAP content. This premium resin provides high elongation and toughness necessary for improved impact resistance. The resin is designed for high performance boats that remain in the water for extended periods of time.

Note: These resins are not designed for chemical corrosion resistance.

Liquid Resin Properties

Typical Liquid Properties at 77°F:

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>VALUE</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brookfield Viscosity</td>
<td>175</td>
<td>cps</td>
</tr>
<tr>
<td>LVT sp 250 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids, %</td>
<td>&gt; 85</td>
<td>%</td>
</tr>
<tr>
<td>Density</td>
<td>8.9</td>
<td>lb/gal</td>
</tr>
<tr>
<td>Monomer</td>
<td>Styrene</td>
<td></td>
</tr>
<tr>
<td>Flash Point Range</td>
<td>73-100</td>
<td>°F</td>
</tr>
</tbody>
</table>

Mechanical Properties

Typical Mechanical Properties at 140°F: Postcured for 2 hours

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>VALUE</th>
<th>UNIT</th>
<th>METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>11,782</td>
<td>psi</td>
<td>ASTM D-338</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>505 x 10⁵</td>
<td>psi</td>
<td>ASTM D-338</td>
</tr>
<tr>
<td>Tensile Elongation</td>
<td>4.2</td>
<td>%</td>
<td>ASTM D-338</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>10,060</td>
<td>psi</td>
<td>ASTM D-790</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>53 x 10⁵</td>
<td>psi</td>
<td>ASTM D-790</td>
</tr>
<tr>
<td>Heat Deflection Temp.</td>
<td>174</td>
<td>°F</td>
<td>ASTM D-648</td>
</tr>
</tbody>
</table>

*Typical values: Based on materials tested in our laboratories, but varies from sample to sample. Typical values should not be construed as a guaranteed analysis of any specific lot or as specification item.
### Appendix D (SuperLite Balsa)

Data Sheet / Issue 09/05 / Replaces Issue 03/05

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Standard</th>
<th>Unit</th>
<th>SL.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent nominal density</td>
<td>ASTM C 271</td>
<td>kg/m³</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lb/ft³</td>
<td>5.1</td>
</tr>
<tr>
<td>Compressive strength perpendicular to the plane</td>
<td>ASTM C 365</td>
<td>N/mm²</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>psi</td>
<td>736</td>
</tr>
<tr>
<td>Compressive modulus perpendicular to the plane</td>
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<td>N/mm²</td>
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<td>Psi</td>
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<td>ASTM C 297</td>
<td>N/mm²</td>
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<td>Tensile modulus perpendicular to the plane</td>
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<td>N/mm²</td>
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<td>Shear strength</td>
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<td>N/mm²</td>
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<td>Shear modulus</td>
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<td>psi</td>
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<td>Thermal conductivity at room temperature</td>
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<td>W/m.K</td>
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<td>BTU/in²·hr·°F</td>
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<td>3/16 to 4</td>
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