2020

Experimental and Field Evaluation of FRP Pedestrian Bridge Decks

Kalrav Singh Tomer
West Virginia University, kalravtomer@gmail.com

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Part of the [Civil Engineering Commons](#), [Mechanics of Materials Commons](#), and the [Structural Engineering Commons](#)

Recommended Citation

Tomer, Kalrav Singh, "Experimental and Field Evaluation of FRP Pedestrian Bridge Decks" (2020).
Graduate Theses, Dissertations, and Problem Reports. 7509.
<https://researchrepository.wvu.edu/etd/7509>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

Experimental and Field Evaluation of FRP Pedestrian Bridge Decks

Kalrav Tomer

Thesis submitted to the College of
Engineering and Mineral Resources at
West Virginia University in partial
fulfillment of the requirements for the
degree of

Master of Science

In

Civil Engineering

P V Vijay, Ph.D., Chair

Radhey S Sharma, Ph.D.

Gloria Oporto, Ph.D.

Morgantown, West Virginia

2020

Keywords: GFRP Deck, Static testing, Fatigue testing, Deflection, Strain, Stiffness, Pedestrian
Bridge

Copyright 2020: Kalrav Singh Tomer

ABSTRACT

Experimental and Field Evaluation of FRP Pedestrian Bridge Decks

Kalrav Singh Tomer

Traditional materials such as steel, timber, and concrete have continued to dominate their usage in civil infrastructure. They offer great advantages like strength and stiffness but at the same time they pose major issues in terms of durability and maintenance. Fiber reinforced polymer (FRP) exhibits outstanding properties like lightness, excellent corrosion and wear resistance along with superior thermo-mechanical properties. Glass FRPs (GFRPs) have emerged as one of the best alternatives in the field of civil infrastructure. It has been more than four decades since fiber reinforced polymer (FRP) composites have gained notable applications in civil infrastructure industry. However, FRPs have found limited applications in bridges, rehabilitation of old structures, complex designs with connections and hybrid structures. Apart from some of the present applications in the civil infrastructure, GFRPs can be extensively used as construction materials for pedestrian bridges due to their high strength to weight ratio, excellent structural behavior under cyclic loading and easy installation. These properties make them even more attractive for various connectivity applications in non-uniform topography where traditional materials may not provide optimum solutions.

In this research, the structural behavior of GFRP (Glass Fiber Reinforced Polymer) decks with different depths are investigated under static and fatigue loads. The suitability of these GFRP decks for mass transit and rapid installation including Pedestrian bridge structures are evaluated. Full-scale GFRP decks with different (a/d) ratios were subjected to static and fatigue loads to determine their overall structural stiffness, strains (stresses) and deformation behavior under cyclic loading. Both 3-point and 4-point bending tests were conducted for different span lengths. The experimental results show that the decks provide a superior structural performance in terms of the load carrying capacity with minimal or no change in the global stiffness over a million cycles of fatigue loading for different strain ranges. Theoretical predictions on structural deformations correlate well with the experimental results. The research further focused on the field implementation and testing of interlocked GFRP decks as a modular system. Both lab and field evaluations showed similar performance results. Results and field evaluation of the FRP pedestrian bridge decks prove their potential and suitability for new construction or replacement of other structural systems such as subway platforms, patios, and docks.

This thesis is dedicated to my late Grandparents.

ACKNOWLEDGEMENTS

I would like to thank everyone who made my masters studies at West Virginia University a fabulous experience that I will never forget.

First, I would like to thank my advisor Dr. P.V. Vijay for the opportunity to extend my education to master's studies in his research group. His expertise, patience, and steadfast assistance helped me to guide my development as a student and a researcher. He has helped me in both personal and professional capacity. I also extend my deepest gratitude to Dr. Radhey S Sharma and Dr. Gloria Oporto for being a part of my M.S. committee and giving me new perspectives to learn from.

I would also like to thank our lab technician Mr. Jerry Nestor for his support during experimentation in Structures Lab. I express my gratitude to my fellow students Krishna Tulasi Gadde, Piyush Soti, Pravin Majjigapu, Robby Tennant, Jacob Hise for their valuable inputs throughout my master's course.

Finally, and most importantly, I thank my family and friends for embedding the importance of education in me and their constant coaching and support in my life.

Table of Contents

1. Introduction.....	1
1.1 Introduction	1
1.2 Background and Literature Review	2
1.2 Objectives	5
1.3 Organization of Thesis	5
2. Materials and Manufacturing Process.....	7
2.1 Introduction	7
2.2 Constituent Materials	8
2.2.1 Resins	8
2.2.2 Fiber	9
2.3 Material Description	11
2.4 Manufacturing Process	12
2.4.3 Pultrusion	12
3. Laboratory Testing	14
3.1 Test Specimens and specimen preparation	14
3.2 Static Testing	18
3.2.1 Introduction.....	18
3.2.2 Static Test Setup	19
3.2.3 Test Procedure	21
3.3 Fatigue Testing	24
3.3.1 Introduction.....	24
3.3.2 Fatigue Test Setup	25
3.3.3 Test Procedure	26
3.4 Failure Test.....	27
3.4.1 Failure Test Setup	27
3.4.2 Test Procedure	28
4. Field Testing and Laboratory Replication	29
4.1 Introduction	29
4.2 Pedestrian Bridge Location and Description:.....	29
4.3 Field Test Setup & Procedure:	31

4.4 Interlocked Deck Laboratory Testing	35
5. Data Analysis and Theoretical Comparisons	41
5.2 Theoretical Calculations and Comparisons.....	41
5.2 Behavior of Stiffness under Fatigue	49
5.3 Analysis of Field Data.....	52
5.3 Analysis of Interlocked Deck Panels in the Laboratory.....	55
5.4 Failure Analysis.....	57
5.5 Buckling Consideration	60
6. Summary and Conclusions	62
6.1 Conclusions	62
6.2 Recommendations for Future Work	63
7. References	64

List of Figures

Figure No.	Description	Page No.
2.1	Classification of Fibers	10
2.2	Different types of glass fabrics	11
2.3	GR250 cross section profile	12
2.4	CP064 cross section profile	12
2.5	GR250 Deck panel 3-d Representation	12
2.6	CP064 Deck panel 3-d Representation	12
2.7	Schematic of Pultrusion Process	13
3.1	Testing specimen Deck#1	15
3.2(a)	Configuration of LVDTs below Deck#1 and Deck#2	16
3.2(b)	Top Face sheet Strain Gauge Layout for Deck#1 and Deck#2	17
3.2(c)	Bottom Surface Strain Gauge Layout for Deck#1 and Deck#2	17
3.3(a)	Configuration of LVDT (LC) below Deck#3	17
3.3(b)	Top Face sheet Strain Gauge Layout for Deck#3	18
3.3(c)	Bottom Surface Strain Gauge Layout for Deck#1	18
3.4(a)	3-point static testing (Elevation View)	19
3.4(b)	3-point static testing (Plan View)	20
3.5(a)	4-point static testing (Elevation View)	20
3.5(b)	4-point static testing (Plan View)	21
3.6	Deflection at full load under 3-point static testing	23
3.7	Deflection at full load under 4-point static testing	23
3.8	Deck#3 Deflection at full load under 3-point static testing	24
3.7(a)	Fatigue testing (Elevation View)	25
3.7(b)	Fatigue testing (Plan View)	26
3.8	Deck#3 Deflection at full load under 3-point static testing	27
3.9(a)	Fatigue testing (Elevation View)	27
3.9(b)	Fatigue testing (Plan View)	28
3.10	Deck#3 in extreme loading during Failure test	28
4.1	Location of Pedestrian Bridge	29
4.2	Bridge Elevation	30
4.3	Steel Framing Plan	30
4.4	GFRP Deck Panel connection	31
4.5	Schematic of GFRP decks considered for field test	32
4.6	Schematic of LVDT placement for field testing	33
4.7	Use of sandbags for providing UDL during field testing	34
4.8	Schematic for sandbag placement	34
4.9	Interlocked deck system in lab	36
4.10(a)	Configuration of LVDT's on Interlocked Deck System	37

4.10(b)	Top Face sheet Strain Gauge Layout for Interlocked Deck System (Top view)	38
4.10(c)	Bottom Face sheet Strain Gauge Layout for Interlocked Deck System	38
4.11	Clamp on the support preventing horizontal movement of the interlocked deck panels	39
4.12(a)	3-point static testing on interlocked GFRP deck system (Elevation View)	40
4.12(b)	3-point static testing for interlocked GFRP deck system (Top View)	40
5.1	Validation of Stiffness Calculation for GFRP Deck	43
5.2	Load-Deflection Plot for Deck#1 at 11ft span length and 3-point bending test	44
5.3	Load-Deflection Plot for Deck#1 at 8ft span length and 4-point bending test	45
5.4	Load-Deflection Plot for Deck#3 at 7ft span length and 3-point bending test	45
5.5(a)	Load-Strain Plot for Deck#1 under 3-point bending	47
5.5(b)	Load-Strain Plot for Deck#1 under 4-point bending	47
5.6(a)	Load-Strain Plot for Deck#2 under 3-point bending	48
5.6(b)	Load-Strain Plot for Deck#2 under 4-point bending	48
5.7	Load-Strain Plot for Deck#3 under 3-point bending	49
5.8(a)	Effect of cyclic load on deflection in Deck#1	50
5.8(b)	Effect of cyclic load on deflection in Deck#2	51
5.8(c)	Effect of cyclic load on deflection in Deck#3	51
5.9	Effect of cyclic loading on Relative Stiffness of GFRP Material	52
5.10	Schematic of an equally overhanging beam with uniformly distributed load	55
5.11	Load-Deflection Plot for Interlocked Deck System	56
5.12	Load-Strain Plot for Interlocked Deck System	56
5.13	Failure location in Deck #1	58
5.14	Load vs Strain curve under failure loading of Deck #1	58
5.15	Failure in legs at mid span Deck #3	59
5.16	Load vs Strain curve under failure loading of Deck #3	59

List of Tables

Table No.	Description	Page No.
2.1	Properties of Vinyl Ester Resin	9
2.2	Mechanical Properties of Glass Fiber	11
3.1	GR250 Deck Properties provided by Creative Pultrusion	14
3.2	CP064 Deck Properties provided by Creative Pultrusion	14
3.3	Instrumentation in Deck#1 and Deck#2 for measurement	15
3.4	Instrumentation in Deck#3 for measurement	16
3.5	Load Values for Deck#1 and Deck#2	22
4.1	LVDTs for deflection measurement during field test	32
4.2	Instrumentation for measurement for Interlocked Deck System	37
5.1	Comparison of E value	42
5.2	Maximum deflection value comparison	43
5.3	Summary of Fatigue Test Scenarios	50
5.4	Comparison of experimental and theoretical deflection for Field Testing of Pedestrian Bridge	54
5.5	Deflection data for Field Testing of Pedestrian Bridge	54
5.6	Deflection data for Interlocked deck system	57
5.7	Evaluation of Buckling load in deck#1 and deck#3	61

1. Introduction

1.1 Introduction

Traditionally, materials such as steel, timber, and concrete are used in mass quantities for buildings, bridges, and other large structural elements. These materials have been used for many years with much success, at the same time they have major issues in terms of durability and maintenance that can limit the effectiveness of a structural system. Some of their obvious shortcomings include corrosion, low strength to weight ratio, and loss of performance due to mechanical as well as thermal fatigue.

Bridges are one of the important structures in civil infrastructure industry. They are subjected to aggressive environments which lead to material failure. The U.S. has 614,387 bridges, almost four in 10 of which are 50 years or older. Among those bridges, 56,007 (9.1%) were structurally deficient in 2016, and on an average, there were 188 million trips across the structurally deficient bridges each day. The most recent estimate puts the nation's backlog of bridge rehabilitation needs at \$123 billion [1]. This overwhelming deficit is attributed principally to corrosion caused by the natural environment and the use of de-icing chemicals. In addition, obsolete highway structures, especially bridges, are also attributed to increasing axle loads and frequencies, coupled with material aging. Due to the large amount of rehabilitation work that needs to be performed, development of new materials more equipped to handle severe traffic and environmental conditions are essential.

The need for innovative construction techniques led to the consideration and evaluation of Fiber Reinforced Polymers (FRPs) which have emerged as one of the best alternatives in the field of civil infrastructure. GFRPs are made primarily of fibers and resins combined in such a way that their composite is stronger than the individual constituents. GFRPs possess low density, better fatigue and corrosion resistance, very high strength to weight properties and superior thermo-mechanical properties [2].

1.2 Background and Literature Review

Hollaway (2010) has reviewed and discussed the development in the applications of GFRP composites materials for buildings and civil infrastructure [3]. The paper discusses the development of the advanced polymer composite material applications in the building and civil/structural infrastructure over the past three to four decades. It focuses on the identification and prioritization of the important research areas which are necessary to improve the understanding of the behavior of FRP materials and FRP structural components. The study demonstrates the types of structures which have been developed from the FRP composite materials and the most advantageous way to employ composites in civil engineering. The FRP with excellent mechanical in-service properties which when combined with other materials can be utilized to improve the stiffness/ strength, durability and life-cycle cost benefits with positive environmental impact.

Comprehensive state-of-the-art report on GFRP composites for construction in civil engineering is presented by Bakis et al. [4]. The paper is organized into separate sections on structural shapes, bridge decks, internal reinforcements, externally bonded reinforcements, and standards and codes. This review attests to the many potential applications of FRP composite materials in construction. It discusses the amount of experience with various forms of FRP construction materials that vary in accordance with the perceived near-term economic and safety benefits of the materials.

Structures are subjected to aggressive environmental conditions like moisture, excessive temperatures, UV, chemicals etc. Several researchers worked on understanding the response of FRP materials under various environmental conditions. The study of Heshmati et al. discusses the durability of the adhesively bonded joints between FRP and steel in the civil infrastructure industry [5]. Important influential factors relating to the durability like moisture and temperature have been discussed in depth. Moreover, the damage mechanism of different bonds has been reviewed. Yan et al. reviews application of cellulosic fibers and their polymer composite in civil engineering [6]. In addition, the degradation mechanisms of cellulosic FRC and FRP such as UV and ageing solutions like water, seawater, alkali are discussed. The researchers recommend

further research on cellulosic FRPs to improve mechanical properties, moisture resistance and composite behavior. A research by Keller and Bai reviews experimental work and modeling to understand the behavior of FRP in fire [7]. The effect of thermal exposure on thermophysical and thermomechanical properties were studied and the degradation in FRP due to fire above certain temperature thresholds of about 200°F are noted.

Fang et al. focus on the structural applications of FRP composites as major load-carrying members in aggressive environments [8]. They review and compare the environmental effects on FRP composites of a structure with respect to joints and connections, including elevated environmental temperatures, humidity and water immersion, and ultraviolet (UV) exposure.

It has been more than a decade since fiber reinforced polymer (FRP) composites have gained some major field implementations in the civil infrastructure industry. FRP's have been investigated for their application as various structural components and systems. In a study by Yang and Bai, pultruded glass FRP (GFRP) materials were used to fabricate "space frame" and then it was subjected to 3-point static testing, fatigue testing, and free vibration testing along with FE modelling which showed the superior performance of GFRPs [9,10].

FRPs became attractive structural materials for various applications in residential and commercial buildings. A paper authored by Zhu et al. investigated the application of sandwich panel GFRP in multistory building [11]. The panels featured a paulownia wood core reinforced by glass fiber reinforced polymer (GFRP) face sheets and web (GFPW), which were manufactured by a vacuum assisted resin infusion process. A four-point bending test was performed to validate the effectiveness of the detailed web configuration in improving the panel stiffness and capacity. The results showed that the bending stiffness and ultimate bending strength could be enhanced by increasing the web thickness, web height, and face sheet thickness, as well as by reducing web spacing. FE studies of innovative GFPW panels implemented in a multistory building were conducted and analyzed for the structural behavior. In addition, failure modes, load-deflection relationships, and load-strain behavior were investigated. A Characterization is conducted by Zafari and Mottaram of pultruded fiber reinforced polymer assembly for the Startlink house [12]. Two joints having beam-to-column dowel connections, with and without extra adhesive bonding

were statically loaded in increments of moment or rotation to final failure. The floor beam and stud column members were bespoke closed sections developed for the Startlink lightweight building system.

Gadat et al. investigates the replacement of traditional materials (steel, wood and concrete) in electricity transmission lines by fiber glass pultruded members [13]. Design of various FRP pultruded sections and cost estimates were conducted for 69 kV electricity transmission portal frames for a total distance of 10 km. It was found that the FRP pultruded circular-sections with 200 m span between frames can be considered as an optimum solution to replace the steel in electricity transmission lines

An overview by Gaudes et al. on composite pile technologies and an examination on the different factors that affect their soil-driving performance [14]. Emphasis on the potential use of hollow fiber reinforced polymer (FRP) piles and the need for further study on their impact behavior is highlighted. The possibility of damaging the fiber composite materials during the process of impact driving is present and the author suggests further research on the impact behavior of this type of composite piles ranging from constituent materials to full-scale levels.

Apart from present applications in the civil infrastructure, GFRP (Glass Fiber Reinforced Polymer) can be extensively used as construction materials for pedestrian bridges due to their high strength to weight ratio, excellent structural behavior under cyclic loading and easy/quick installation. These properties make them even more attractive for various connectivity applications in non-uniform topography where traditional materials have failed to provide optimum solutions. Israel, in 1975, built first pedestrian GFRP bridge deck in Tel Aviv [15]. A bridge built of composite materials can be constructed and put into service in a relatively short time and at a competitive cost. Its lightweight and ease of construction provide large labor and traffic control cost savings to offset a higher first cost. Bank published a state-of-the-Art review of composites for highway bridge applications [16].

In this research, we have experimentally evaluated the behavior of two different kinds of GFRP panels suitable for pedestrian bridge deck applications under static and fatigue loads. The decks

were manufactured by Creative Pultrusion [17] and were field implemented following the laboratory evaluations. The findings of this research will be beneficial to assess the application of these light weight GFRP decks as primary structural members in new construction including pedestrian bridges, subway platforms, patios and docks, moving bridges and in many other applications.

1.2 Objectives

The primary goals of this research are to investigate the structural behavior of GFRP decks manufactured by the pultrusion process and field implement them. The objectives of this work are to:

- 1) Lab evaluate the behavior of GFRP deck panels by conducting static and fatigue load tests to determine their suitability for pedestrian bridge applications.
- 2) Test the decks up to their failure loads and observe the failure modes and failure locations including serviceability limits of deflection.
- 3) Field install one of the GFRP deck panel types evaluated in the lab as a pedestrian bridge.
- 4) Field test the installed pedestrian GFRP deck panels under design live loads.
- 5) Compare the experimental and field tests with analytical models.

1.3 Organization of Thesis

Chapter 2 describes the properties of the constituent materials used for the GFRP decks and the manufacturing processes with emphasis on Pultrusion process.

Chapter 3 focuses on the experimental work including test specimens, specimen preparation, test set-up and test procedure under static and fatigue loads.

Chapter 4 provides the details on field testing of the pedestrian bridge with the GFRP decks evaluated in this study.

Chapter 5 includes the test results and theoretical analysis along with the comparison of field and lab test results.

Chapter 6 presents the summary and conclusions of this study and recommendations for future work.

2. Materials and Manufacturing Process

The chapter discusses the details of the GFRP (Glass Fiber Reinforced Polymer) deck panels used in this study, which involves an understanding of the constituent materials and fabrication through pultrusion process for the GFRP decks manufactured by the Creative Pultrusion Inc. [17]. Some of the most important properties in determining the performance of polymer composites materials are their strength and stiffness values. In this research, we are evaluating the performance of FRP decks by subjecting them to static and fatigue loads to evaluate their strength and stiffness properties. There are various American Concrete Institute (ACI), American Society of Civil Engineers (ASCE), Elsevier and other journal and conference publications that extensively deal with the micro-mechanics, behavior, and application of FRP composites for structural applications. This Chapter only focuses on the materials and manufacturing processed used for the manufacturing of FRP pedestrian bridge decks used in this study.

2.1 Introduction

Polymer composites are described as high-performance and versatile materials formed from a combination of resins and fibers. The merits of composites are the complementary nature of the constituents. Generally, the tensile strength and stiffness of the fiber materials are much higher than the resin material, which makes the fiber as the major load-bearing component in polymer composites. However, the matrix helps in distributing the load uniformly to the fiber. The bonding of fiber and matrix results in proper load transfer, thus increasing the composites mechanical properties [18].

The performance of polymer composites is generally determined by:

1. the properties of the fiber
2. the properties of the resin (polymer matrix)
3. the ratio of the fiber to the polymer matrix in the composite (fiber volume fraction)
4. the geometry and orientation of the fibers in the composite

The mechanical, physical and chemical properties of the polymer composites physical, chemical and mechanical properties play a vital role in their application for construction industry. As the

fibers the mechanical properties are much higher than those of resins, the higher the fiber volume fraction the higher will be the mechanical properties of the resultant composite. Normally, with the use of a common hand lay-up process, which is broadly used in the boat-building industry, fiber volume fraction is approximately 30-40%. With higher manufacturing quality, more sophisticated and precise processes are used in the aerospace industry with fiber volume fractions approaching 70% as mentioned in the study of Shekar [2007].

The geometry of the fibers in a composite is vital because fibers exhibit higher mechanical properties along their lengths, rather than across their widths. This results to the high composites anisotropic properties, however, in case of metals they are isotropic in nature. Composites mechanical properties are different when tested in different directions. This explains, at the design stage it is important to consider the way of use of composites for structural applications in both the magnitude and the direction of the applied loads.

If these properties are optimally used, the anisotropic properties of composites can be very advantageous since the placement of the material is only necessary where the load is applied and thus the use of extra material can be ignored

2.2 Constituent Materials

Fiber reinforced polymer (FRP) composites are made of two essential constituents like resin and fibers. Apart from these two constituents, it also consists of additives and small quantities of coatings, pigments, and fillers. The additives include plasticizers, impact modifiers, heat stabilizers, antioxidants, light stabilizers, flame retardants, blowing agents, antistatic agents, coupling agents, and others [18].

2.2.1 Resins

The resins can be broadly classified as thermoplastic and thermoset polymers. Thermoplastic polymers under heat can be remolded often upon reheating while thermoset polymers are in liquid state during initial stage of manufacturing but will not melt again upon reheating. Examples of thermoplastic polymers include polyethylene, polypropylene, polystyrene, ABS etc. Epoxy, polyester, vinyl ester, and urethane are some of the examples of thermoset polymers. Proper

resin selection is based on the service conditions and required durability of the end-product and should consider the temperature, humidity, chemical environment, and pH of the liquid or gas in contact with the manufactured profiles. Virtually all the physical properties (chemical, electrical, and thermal) are strongly influenced by the resin.

The test specimens used in this research are made of fire-retardant resin Vinyl Ester (VE) resins. Vinyl Ester (VE) Resins are based on bisphenol-A epoxy resins. VE resins provide resistance against a wide range of acids, alkalis, bleaches and solvents for use in many chemical environments. They also offer excellent toughness and fatigue resistance. VE resins are more flexible, possess higher toughness, durable, chemically resistant and have low viscosity. Vinyl ester resins typically possess the following advantages, disadvantages, and properties as shown in Table 2.1 [17].

Table 2.1: Properties of Vinyl Ester Resins [17]

Typical Properties		Advantages	Disadvantages
Tensile Modulus (Ksi)	500	Freeze-Thaw resistant	Alkalinity Resistance
Tensile Strength (Ksi)	12	Salt Resistant	
Compressive Strength (Ksi)	17	Very Durable	Up to \$1.8/ lb.
Shear Strength (Ksi)	12	Fatigue Resistant	Moisture Uptake
Tensile % Elongation	5-6	Excellent Corrosion Resistance	Minor Pultrusion Problems
Flexural Modulus (Ksi)	490		
Flexural Strength (Ksi)	18	Resistant to multiple attacks, simultaneously	Weakens Above 200 F
Poisson's ratio	0.38		

2.2.2 Fiber

Fiber gives the great tensile strength in FRP when cured with the resin. Fibers are classified in two categories- Natural Fibers and Synthetic fibers. The classification of fibers is briefly described in Libo et al. (2016), Figure 2.1 shows the classification of fiber.

Figure 2.1 Classification of Fibers [6]

In Civil Industry, mostly synthetic fibers are used. Carbon, Glass, Aramid, Boron are predominant types of fibers typically used in the construction industry. The most important properties that differ between the fiber types are stiffnesses, strengths, failure strains and their durability. Fibers can be available in different forms like strands, rovings, tow and yarns. Depending on the construction and orientations, fiber/fabrics are classified into unidirectional (1D), mat, multidirectional (2D) and advanced fabrics (3D). Fibers are the load-carrying constituents of composites and occupy the largest volume in a composite laminate. They are produced in many different forms to suit various industrial and commercial applications. Although any of these materials can be used to create composite materials, this report will briefly discuss about glass fibers which were used in the fabrication of the test specimen [18].

Mechanical properties of various types of glass fiber as mentioned in book authored by Wallenberger et al. [20] are listed in Table 2.2.

Table 2.2: Mechanical Properties of Glass Fibers [20]

Fiber Type	Density (g/cm³)	Tensile Strength (Mpa)	Modulus (Gpa)	Percent Elongation
A-Glass	2.44	3300	72	4.8
AR-Glass	2.7	1700	72	2.3
C-Glass	2.56	3300	69	4.8
D-Glass	2.11	2500	55	4.5
E-Glass	2.54	3400	72	4.7
ECR-Glass	2.72	3400	80	4.3
R-Glass	2.52	4400	86	5.1
S-Glass	2.53	4600	89	5.2

Glass fibers offer many advantages, such as:

1. Low cost
2. High tensile strength
3. High chemical resistance
4. Excellent insulating properties

The drawbacks of glass fibers are:

1. Low tensile modulus
2. Relatively high specific gravity
3. Sensitivity to abrasion from handling
4. High hardness
5. Relatively low fatigue resistance

2.3 Material Description

The deck manufactures by Creative Pultrusion Inc. used in this study is suitable for outdoor applications including pedestrian bridge decks. There was a total of three number of decks which were evaluated under this study. Two types of decks of same size 12'4" X 2' with and without surface coatings designated as GR250 and a third type smaller deck with a size of 7'11" X 10^{1/4}" designated as CP064 were used in this study.

The 2-dimensional cross sections profiles of GR250 and CP064 are shown in Figure 2.2 [17] and Figure 2.3 [17] respectively. The 3-D representation of the deck is shown in Figures 2.4 and 2.5.

Figure 2.3. GF250 cross section profile [17]

Figure 2.4. CP064 cross section profile [17]

Figure 2.5. GR250 Deck panel

Figure 2.6. CP064 Deck panel [17]

The stiffness in the panel is derived from the inbuilt C-sections and W-sections below the surface sheet during the pultrusion process. The provision of these sections makes the panel stiffer by generating higher moment of inertia.

2.4 Manufacturing Process

The different methods of manufacturing include pultrusion, compression molding, bladder molding, mandrel wrapping, autoclave, filament winding, and wet layup, amongst others.

These GFRP decks used in the current research are manufactured by Pultrusion. It is the most popular method of FRP production which is further described in the following section.

2.4.3 Pultrusion

Pultrusion is a manufacturing process which is utilized for making composites sections of required uniform cross sections and lengths with the use of FRP mats and rovings. Pultrusion process is used to fabricate continuous FRP structural shapes without altering their cross-sections. There are multiple variations of the pultrusion process, ranging from the use of a reciprocating puller to a caterpillar puller, but the basic concept is mostly the same across all processes.

The schematic of pultrusion process is shown in Figure 2.6 [19]:

Figure 2.7: Schematic of Pultrusion Process [19]

Following are the steps in Pultrusion process:

1. Glass fibers are pulled from the spools by the guides in the resin bath and are saturated in the resin while the alignment of the fiber is firmly maintained.
2. The fibers are passed through the forming fixtures which eradicate excessive resin and vacuum, at the same time the fibers are being grouped into their stipulated shape.
3. The fibers are being pulled into the heating sections where they are being cured. The curing happens at certain temperature ranges while the part is being pulled through the section.
4. The final product is then pulled out from the heating section where the curing is carried out.
5. The cured part is passed through pullers and the product is cut to a stipulated length.

For this research, two types of full-scale deck panels of dimensions 12.25'x 5" X 24" and 8'x 2" X 10¼" were pultruded, tested, and field implemented as described in the next Chapters 3 to 5.

3. Laboratory Testing

As per the objectives of this research, the stiffness of the GFRP (Glass Fiber Reinforced Polymer) deck and its behavior under the cyclic loads were evaluated. This chapter describes the configuration of test specimen, test set up and procedure for evaluation of the GFRP decks.

3.1 Test Specimens and specimen preparation

The GFRP Decks were manufactured by Creative Pultrusions, Inc. The decks are designated as GR250 and CP064 by the manufacturer. The GR250 decking is 1/5th the weight of a concrete deck, easily attaches to the steel structure, and accommodates the thermal expansion requirements. The CP064 is stronger and 70% lighter than steel and will not rot, rust or spall. Tables 3.1 and 3.2 show the physical and mechanical properties of the two types of decks.

Table 3.1: GR250 Deck Properties provided by Creative Pultrusion

Notation	Description	Value	Unit
E_b	Youngs Modulus (stiffness)	3.5	Msi
I_x	Moment of Inertia	41.2	in ⁴ /ft
A_w	Web area	3.9	in ² /ft
G_b	Shear Modulus	0.5	Msi
S_x	Section Modulus	13.3	in ³ /ft
W_e	Weight	9.4	psf
F_L^C	Characteristic longitudinal compressive strength	30000	psi
F_{LT}^V	Characteristic in-plane shear strength	10000	Psi
W	Width	2	in
L	Length	12.333	ft

Table 3.2: CP064 Deck Properties provided by Creative Pultrusion

Notation	Description	Value	Unit
E_b	Youngs Modulus (stiffness)	3.5	Msi
I_x	Moment of Inertia	2.86	in ⁴ /ft
A_w	Web area	3.30	in ² /ft
G_b	Shear Modulus	0.43	Msi
S_x	Section Modulus	2.43	in ³ /ft
W_e	Weight	5.47	psf
F_L^C	Characteristic longitudinal compressive strength	45000	psi
F_{LT}^V	Characteristic in-plane shear strength	4500	Psi
W	Width	10.25	in
L	Length	7.917	ft

Two similar GR250 decks with and without the wearing surfaces were evaluated. The deck with the wearing surface is identified as “**Deck#1**” and the deck without the coating surface was identified as “**Deck#2**” for the experimental work conducted during this research, and the other deck with different configuration (CP064) is identified as “**Deck#3.**” Figure 3.1 shows the three types of deck specimens evaluated in this study.

(a)Deck #1

(b)Deck #2

(c)Deck #3

Figure 3.1: Different Deck Specimens

Before testing, specimens namely Deck#1, Deck#2 and Deck#3 were instrumented with strain gages and LVDTs for measurement purpose. LVDTs measure the linear deflections and strain gauges measure the strains. List of the LVDTs and strain gages installed on Deck#1 and Deck#2 are provided in Table 3.3. Table 3.4 lists the details of instrumentation on Deck#3.

Table 3.3 Instrumentation in Deck#1 and Deck#2 for strain and deflection measurement

Instrumentation	Name	Location
Strain Gauge	TLC	Top Longitudinal Center
Strain Gauge	TLS	Top Longitudinal Side
Strain Gauge	TT	Top Transverse Center
Strain Gauge	BLC	Bottom Longitudinal Center
Strain Gauge	BLS	Bottom Longitudinal Side
LVDT	LC	Center Deflection
LVDT	LS	Side Deflection

Table 3.4 Instrumentation in Deck#3 for strain and deflection measurement

Instrumentation	Name	Location
Strain Gauge	TLC	Top Longitudinal Center
Strain Gauge	TT	Top Transverse Center
Strain Gauge	BLC	Bottom Longitudinal Center
Strain Gauge	BLS	Bottom Longitudinal Side
LVDT	LC	Center Deflection

Instrumentation for the test specimens is shown in Figure 3.2 (for **Deck#1** and **Deck#2**) and Figure 3.3(for **Deck#3**). Figure 3.2(a) indicates the two LVDTs used to record the vertical deformation of the deck at midspan, with a LVDTs positioned along the deck centerline and deck I section. Strain gauges were installed along the top and bottom surfaces of the panels as shown in Figures 3.2(b) and 3.2(c). A series of strain gauges were placed at midspan of the deck. Gauges TLC & TLS measured longitudinal strain and Gauge TT measured transverse strain of the top surface of the deck. Gauges BLC and BLS measured longitudinal strain of bottom surface of deck. All the instrumentation was recorded through a data acquisition system. Similarly, for Deck#3 Figure 3.3(a) shows the location of LVDT placed for deflection and Figure 3.3(b) and (c) shows the location of Strain gauges.

Figure 3.2(a): Configuration of LVDTs (LV and LC) below Deck#1 and Deck#2 (notations in Table 3.3)

Figure 3.2 (b): Strain Gauge (TLS, TLC and TT) Layout at the top surface for Deck#1 and Deck#2 (notations in Table 3.3)

Figure 3.2 (c): Strain Gauge (BLS and BLC) Layout at the bottom surface for Deck#1 and Deck#2 (notations in Table 3.3)

Figure 3.3(a): Configuration of LVDT (LC) below Deck#3 (notations in Table 3.4)

**Figure 3.3(b): Strain Gauge configuration of LVDT (TLC) at the top surface for Deck#3
(notations in Table 3.4)**

**Figure 3.3(c): Strain Gauge (BLS and BLC) Layout at the bottom surface for Deck#3
(notations in Table 3.4)**

3.2 Static Testing

“Static testing” was used to measure the strength and stiffness of GFRP deck components. Adequate strength is necessary to prevent deck failures while high stiffness is necessary to minimize deflections. This section presents the simplified analytical models used for calculating Young’s Moduli in longitudinal direction of the decks.

3.2.1 Introduction

Static testing was performed in with different span lengths. GFRP Deck#1 and Deck#2(24” wide x 5” deep) were subjected to 3-point bending load with 6 ft, 8ft and 11 ft span lengths. The load was applied for each span length such that a bending moment of ~40 k-ft was applied at the midspan. The moment of 40 k-ft corresponds to a uniformly distributed load (UDL) of 2500 psf as compared to the required design load of 100 psf (live load) for the pedestrian bridge deck. For Deck #3 (10.25” wide x 2” deep), a test span of 7 ft was used and a moment of 1.75 k-ft was applied at the center. The moment of 1.75 k-ft corresponds to a uniformly distributed load (UDL) of 335 psf as compared to the required design load of 100 psf (live load) for the pedestrian bridge deck.

3.2.2 Static Test Setup

Figure 3.4 shows a schematic of the 3-point static test setup. Concrete-filled steel tube were used to provide a roller support. Concrete walls beneath the rollers support the specimen at the required height within the load frame. Loads were applied to the deck panel through a 300kip capacity MTS hydraulic press and a loading jack. A 40-kip capacity load cell was positioned between the loading jack and the steel block to measure and record the applied loads. The applied load was distributed to the deck through a 2-in.-thick and 4-in.-wide steel plate measuring 24 in. in length. A 0.5-in.-thick neoprene pad was placed between the steel plate and the deck surface to prevent any stress concentrations at the loading point. The loading application was at the midspan perpendicular to the deck span in order to maximize the flexural stresses in the panel.

Figure 3.4(a): 3-point static testing (Elevation View)

Figure 3.4(b): 3-point static testing (Plan View)

A schematic of the 4-point static test setup is shown in Figure 3.4. The deck specimen was supported at each end by a concrete-filled steel tube to provide a roller support. Loads were applied to the panel through a 300kip capacity MTS hydraulic press and a loading jack. A 40kip capacity load cell was positioned between the hydraulic press and the steel blocks to measure and record the applied load. The applied load was distributed to the deck through a 2-in.-thick steel plate measuring 10in square in cross-section.

Figure 3.5(a): 4-point static testing (Elevation View)

Figure 3.5(b): 4-point static testing for Decks #1 and #2 with overhang of excessive lengths (Plan View)

3.2.3 Test Procedure

As discussed earlier, the tests were performed under 3-point & 4-point static testing on Decks #1 and #2 with 6 ft, 8ft and 11 ft span lengths. The loads were applied such that a bending moment of ~40 k-ft was applied for 3-point testing and 4-point testing at midspan for Decks #1 and #2. For Deck#3, there was only 3-point bending test with a mid-load load of 1kip (1000 lbs.)

For 3-point loading, moments for a point load at mid-span are calculated as:

$$M_{\max} (\text{at midspan}) = \frac{W L}{4}$$

Where, $M_{\max}$ is the bending moment at the midspan

W is the concentrated load applied at midspan

L is the deck span length

For 3-point loading, moments for a point load at mid-span are calculated as:

$$M_{\max} (\text{at midspan}) = \frac{W L}{6}$$

Where, $M_{\max}$ is the bending moment applied at midspan

W is the concentrated load applied at midspan

L is the deck span length

Table 3.3 below lists all the calculated load values for 3-point and 4-point tests for 6ft, 8ft and 11ft deck span to obtain a moment of 40 k-ft.

Table 3.5: Load Values for Deck#1 and Deck#2

Deck#1 & Deck#2	L	M	W
	(ft)	(kip.ft)	(Kip)
3-point	6	40	26.6
3-point	8	40	20
3-point	11	40	14.5
4-point	6	40	39.9
4-point	8	40	30
4-point	11	40	21.7

Following steps and procedures followed during the static testing:

1. Selection of desired deck specimen and span length for a given configuration of the loading system
2. Connection of all the attached instrumentation to data acquisition system for automatic data collection purposes
3. Increase of the load application from zero to predetermined maximum load (W) and visual inspection of the deck during loading
4. Decrease of the load from maximum (W) to zero and visual inspection of the deck
5. Data collection from data acquisition system.

Figures 3.6 and 3.7 show the behavior and deflections at maximum loading under 3-point, 4-point static testing respectively for Deck#1 and Deck#2.

Figure 3.8 shows the load application under 3-point static testing for Deck#3.

Figure 3.6: Deflection at full load under 3-point static testing

Figure 3.7: Deflection at full load under 4-point static testing

Figure 3.8: Deck#3 Deflection at full load under 3-point static testing

3.3 Fatigue Testing

Fatigue testing was performed by applying cyclic loading to a test specimen, component or system under consideration to produce fluctuating strains (stresses), which may result in the degradation of material stiffness or strength in addition to the formation of cracks or complete fracture after the application of a certain number of cycles. The fatigue life of a material or a structural element is the total number of cycles that a material or element can be subjected to under a given loading scheme. A fatigue test is also used for the determination of the maximum stress/strain range that a sample can withstand for a specified number of cycles under given set of conditions. All these characteristics are extremely important in any industry where a material is subjected to varying (fatigue) loads.

3.3.1 Introduction

Fatigue testing was performed for two different spans under 3-point bending loads. GFRP Deck#1 with an 8 ft span was subjected to a fatigue load under 3-point bending. Similarly, Deck#2 with a

11ft span was subjected to a fatigue load under 3-point bending. The maximum load was selected such that a maximum bending moment of ~40 k-ft was applied at midspan for Deck#1 and Deck#2. For Deck #3, a test span of 7 ft was used for the application of bending loads under fatigue loading.

3.3.2 Fatigue Test Setup

A schematic of the fatigue test setup is shown in Figure 3.9. The GFRP deck panels were tested under three-point loading (MTS hydraulic press at midspan). The deck specimens were supported and loads from the loading jack were applied in the same way as discussed under static testing. The cyclic loading consisted of a load range of 10 -20kip for Deck#1 and 5kip to 14.5kip for Deck#2, which were maintained for a million cycles at a frequency of 1.5 Hz. A million cycles of loading exceed the expected number of fatigue loading for these decks over a period of 100 years with the majority of load application being in summer months. The number of test cycles also fits within the available time frame and resources to complete the tests during the unprecedented times of lab closures during the CoVid-19 pandemic situation. For Deck#3, the span was kept at 7 ft. with the cyclic loading ranging from 500-1000 lbs. at 1.5 Hz frequency for a million cycles.

Figure 3.9(a): Fatigue testing (Elevation View)

Figure 3.9(b): Fatigue testing (Plan View)

3.3.3 Test Procedure

As mentioned in the introduction of this section, GFRP Deck#1 with 8ft span length was subjected to 3-point bending load. The maximum load was selected such that bending moment of 40 k-ft was applied at midspan at maximum load. As explained in section 3.2.3, we selected 20 kip (W_{max}) as the maximum load for fatigue testing of Deck#1 and the minimum load was selected as 10 kip (W_{min}).

Similarly, Deck#2 with 11ft span length was subjected to 3-point bending load where maximum load was selected such that bending moment was 40 k-ft at midspan of Deck#2. To generate the required bending moment and cyclic operations, a maximum load of 15kip (W_{max}) and a minimum load of 5 kip (W_{min}) was selected.

Similarly, Deck#3 (10.25" wide x 2" deep) with 7ft span length was subjected to a 3-point bending load where the maximum load was 1000 lbs. The load on this deck was selected on the basis of limiting maximum strains in the deck to be ~4000 micro strains.

Following steps and procedures were followed during the fatigue testing of Decks#1 and #2.

1. Selection of desired deck specimen and span length for a given configuration of the loading system
2. Connection of all the attached instrumentation to data acquisition system for automatic data collection

3. Increase of the load application from zero to predetermined maximum load (W_{max}) and visual inspection of the deck during loading
4. Increase the load from zero load to maximum load (W_{max}) and perform visual inspection of the deck and collect the strain and deflection data
5. Fluctuate load application (fatigue) from W_{max} to W_{min} in cyclic manner
6. Stop the fatigue loads at intervals of 50k, 100k, 250k, 750k and 1000k cycles to perform static load testing and perform visual inspection of the deck including the strain and deflection data collection
7. Data collection from data acquisition system.

Above described procedure was used for the fatigue testing of Deck #3 with a load range of 0.5-1 kip, and the intermittent static testing were conducted as described in the test procedure.

3.4 Failure Test

The GFRP decks Deck #1 (GR250) and Deck #3 (CP064) panel were tested up to failure under a central point load as shown in Figure 3.10. Behavior of the deck under the applied loads up to failure is discussed in Chapter 5. Following the test, different failure locations and the mode of failure were observed and recorded.

3.4.1 Failure Test Setup

The failure test setup for Deck #1 and Deck#3 is same as that of the static test. However, to protect the sensitive LVDT during the test and any potential falling of the deck after failure, wooden planks were kept beneath the deck. Deflection in the deck and strains in various parts of the deck at different loads were recorded by the data acquisition system connected with the LVDT and strain gages.

Figure 3.10. Deck #3 in extreme loading during Failure test.

3.4.2 Test Procedure

The following steps and procedures were followed for the failure tests.

1. The deck panel was positioned under the hydraulic jack with the required span of (11ft. for deck #1 and 7ft. for deck #3.)
2. Connection of all the attached instrumentation to data acquisition system for automatic data collection
3. Increase the load from zero load to maximum load (W_{max}) and perform visual inspection of the deck and collect the strain and deflection data
4. Data collection from data acquisition system.
5. Observation of the various failure modes in the deck.

Chapter 4 describes the results of laboratory testing, field implementation of the pedestrian deck types (#1 and #2) and field testing.

4. Field Testing and Laboratory Replication

4.1 Introduction

The laboratory tested pedestrian GFRP (Glass Fiber Reinforced Polymer) deck panels were field installed and their overall performance were evaluated through instrumented field testing. To simulate the field installation, the deck configuration of Deck#1 & Deck#2 were interlocked and subjected to static and fatigue loading in the laboratory as well.

4.2 Pedestrian Bridge Location and Description:

The pedestrian bridge was constructed in WVU Jackson's Mill location which is owned by the WVU Extension Service. It is situated in Lewis County near Weston city. The purpose of the bridge was to give a better connectivity and access to council circle of the WVU Extension Service for the use of K-1 to K-12 students and the residents with disabilities including a safer passage for the visitors and providing an inclusive environment. The project was funded by the WVU Extension Service and the bridge design and installation was coordinated with the help of WVU physical plant and VanNostrand Architects. Figure 4.1 shows satellite location and actual location of Jackson's Mill pedestrian bridge.

Figure 4.1: Location of Pedestrian Bridge

As shown in Figure 4.2, the bridge has 3-spans (40-24-40 ft) with a cumulative length of 104 ft with no skew. The structure is a hybrid, made up of FRP composite decks situated on steel stringers. The bridge is lined with metal railings and vertical posts, which are further connected the wooden and metal roofing. The whole structure is supported on the concrete abutments and piers. The deck passage is 10 feet wide on the end spans whereas the midspan is 14 feet wide.

The walkway through the bridge is enclosed by steel railings and a wooden roof sheeting which makes it safe for the pedestrians with a minimum headroom of 9 ft.

Figure 4.2: Bridge Elevation (courtesy: VanNostrand Architects)

The bridge consists of six W18X76 steel girders which were placed in a parallel manner in the outermost span of 40 ft. and innermost span of 24 ft. at a spacing of 8 feet apart (center to center). For further stiffening of the frame, those girders were connected with W12x16 steel beams (8 feet in length) in the transverse direction at a distance of 8 feet (center to center) from each other as shown in Figure 4.3. The transverse beams are further braced with L4X4X1/4 L section angles. This steel framing system is stiff enough to withstand both vertical and horizontal applications of dead loads, live loads, snow loads and wind loads. The GFRP decks are connected to the steel girders using special FRP/steel anchor clips. At every 8 feet interval along the span, there GFRP decks are interlocked at four locations as shown in Figure 4.4. The whole Frame is supported on the concrete (4000 psi compressive strength) abutments and piers.

Figure 4.3: Steel Framing Plan (courtesy: VanNostrand Architects)

Figure 4.4: GFRP Deck Panel connection underneath the FRP panels

The roof frame consists of W18 members with 4X4 rigid sections. The roof frame includes 4X4X1/4 purlins and eaves which hold the wooden ceiling boards and a protective metal sheeting on the top.

Every year, around 5000 students access this pedestrian bridge in the WVU Jackson's Mill during their camping and learning activities scheduled in summer. So, the bridge is being utilized at its peak during the summer. The bridge is designed to accommodate a minimum live load of around 100 psf and a 2000 lbs. of concentrated load on each panel measuring 2 ft. in width and 11 ft. in length.

4.3 Field Test Setup & Procedure:

The designed load for the pedestrian bridge is 100 psf according to AISC SEI-17. On the pedestrian bridge, we identified two interlocked deck panels designated as "Deck#A" and "Deck#B" for testing purposes. The load was applied on Deck#A and the deflections were measured across 4 locations on both Deck#A and Deck#B. Figure 4.5 shows schematic diagram of GFRP decks considered for field testing.

Figure 4.5: Schematic of GFRP decks considered for field test

Before testing, Deck#A and Deck#B were prepared with installation of strain gages. LVDT's were attached to measure linear deflections. Strain measurements were found to be very small and are not discussed in great detail in Chapter 5. List of LVDTs installed on Deck#A and Deck#B are provided in Table 4.1. Figure 4.6. shows that the two LVDTs were used to record the vertical deformations of the Deck#A and two other LVDTs were used to record the vertical deformations of the Deck#B.

Table 4.1: LVDTs for deflection measurement during field test

Instrumentation	Name	Deck #	x* (in.)	Location
LVDT	D1	A	16	Below surface sheet
LVDT	D2	A	18.4	Below I section interlocked face
LVDT	D3	B	18.5	Below I section interlocked face
LVDT	D4	B	21	Below surface sheet

*x – distance from mid span

Figure 4.6: Schematic of LVDT placement for field testing (notations in Table 4.1)

As mentioned earlier, the load requirement of the pedestrian bridge is 100 psf of uniformly distributed load on Deck#A according to AISC SEI-17. The uniformly distributed load was applied in the form of sandbags with known weights. Each sandbag had a dimension of 1ft x 2ft and weighed 50 lbs. The deck has a dimension of 10ft x 2ft. So total load requirement for the deck is 2000 lbs which was applied with 40 sandbags. Figure 4.7 shows the application of uniformly distributed loads with the help of sandbags for field testing.

Figure 4.7: Use of sandbags for providing UDL during field testing

Based on the 2 ft. width of the deck and geometry of sandbags, we can see that the 100 psf of rated load for each pedestrian bridge deck panel works out to be 200 lb/ft along the length of the deck. Considering the same width of deck and sandbag, we could comfortably stack 4-layers of 50 sandbags along the length of the deck to provide the necessary load of 200 lb/ft (100 psf). Figure 4.8 shows the schematic diagram of the sandbag placement.

Figure 4.8: Schematic for sandbag placement.

Following steps and procedure were used for field testing:

1. Identification of Deck#A and Deck#B for field testing.
2. Preparation and positioning of 4 LVDT's to measure deflections and attachment of strain gages.
3. Provide a layer of sandbag along the length of the deck to provide 50 lb/ft (25 psf of UDL), to measure the strain and deflections.
4. Provide second layer of sandbag along the length of the deck to provide a total of 100 lb./ft (50 psf of UDL) and measure the strains and deflections.
5. Provide third layer of sandbag along the length of the deck to provide total 150 lb./ft (75 psf of UDL) and measure the strains and deflections.
6. Provide fourth layer of sandbag along the length of the deck to provide total 200 lb./ft (100 psf of UDL) and measure the strains and deflections.
7. Unload the sandbags in the reverse order of loading and record the strains and deflections.

The FRP decks instrumented and tested in the field didn't show any significant amount of deflections and strains under the 100% design live load of (100psf or 200 lb./ft load) for which it is designed for. The interlocked deck system in the field situation was tested in the lab as described in the next section.

4.4 Interlocked Deck Laboratory Testing

Similar to the field bridge deck configuration and testing of pedestrian bridges, laboratory tests were conducted to mimic the loading on interlocked panel joints. To replicate this scenario, Deck#1 and Deck#2 were interlocked and subjected to static and fatigue testing in the laboratory. Figure 4.9 shows interlocked deck system in the laboratory. The interlock was achieved by attaching the two decks with preexisting joining schemes and the use of clamps on the roller supports to prevent their horizontal movement and allow their vertical movement as shown in Figure 4.10.

Figure 4.9: Interlocked deck system in lab with an insert of the closeup view

Prior to testing, interlocked deck system consisting of Deck#1 and Deck#2 was prepared with installation of strain gages and LVDTs. The load was applied on Deck#1 and the corresponding strains and deflections were measured both the decks similar to the field testing. List of instrumentations installed on interlocked deck system is provided in Table 4.2.

Table 4.2 Instrumentation for measurement for Interlocked Deck System

Instrumentation	Name	Deck #	Location
Strain Gauge	TLC	1	Top surface, Longitudinal Center
Strain Gauge	TLS	1	Top surface, Longitudinal Side
Strain Gauge	TT	1	Top Surface, Transverse Center
Strain Gauge	BLC	1	Below facesheet, center of the deck (compression side)
Strain Gauge	BLS	1	Below mid I Section (Tension side)
Strain Gauge	S1	1	Below side facesheet (compression side)
Strain Gauge	S2	1	Below I section interlocked face (Tension side)
Strain Gauge	S3	2	Below I section interlocked face
Strain Gauge	S4	2	Below facesheet (compression side)
LVDT	L1	1	Below facesheet (compression side)
LVDT	L2	1	Below mid I Section (Tension side)
LVDT	L3	1	Below side facesheet (compression side)
LVDT	L4	1	Below I section, interlocked face (Tension side)
LVDT	L5	2	Below I section, interlocked face
LVDT	L6	2	Below side facesheet (compression side)

As per Figure 4.10(a), six LVDTs were used to record the vertical deformation of the deck at the midspan, with LVDTs positioned along the deck centerline underneath the I-section of the deck panel. Strain gauges were installed along the top and bottom surfaces of the panels as shown in Figures 4.10(b) and 4.10(c). All the readings from the instrumentation were recorded through a data acquisition system.

Figure 4.10 (a): Configuration of LVDT's on Interlocked Deck System (notations in Table 4.2)

**Figure 4.10 (b): Top Face sheet Strain Gauge Layout for Interlocked Deck System (Top view)
(notations in Table 4.2)**

**Figure 4.10 (c): Bottom Face sheet Strain Gauge Layout for Interlocked Deck System
(notations in Table 4.2)**

Static testing was performed on interlocked deck system with 8ft span length. The Deck#1 of interlocked deck system was subjected to 3-point bending test with concentrated load at center. The maximum load of 10 kip was applied. During field testing, we provided maximum uniformly

distributed load of 200 lb/ft. This uniformly distributed load is equivalent to 0.8 kip of concentrated load at applied at center of deck. Thus, we can see that, during laboratory testing, we provided point load which exceeds the design load for pedestrian bridge. When the load is provided on one deck so to resist the vertical movement of the other interlocked deck the clamps were provided as shown in Figure 4.11.

Figure 4.11 Clamp on the support preventing horizontal movement of the interlocked deck panels

Figure 4.11 shows a schematic of the 3-point static test setup for the interlocked deck system and the static and fatigue loads were applied similar to the procedure described earlier. The loads were applied to the deck through a 2-in.-thick and 4-in.-wide steel plate measuring 24 in length. A 0.5-in.-thick neoprene pad was placed between the steel plate and the deck surface to prevent any localized stress concentrations under the loading point. The loading point was positioned at midspan of the Deck#1 along the panel centerline in order to maximize the flexural stresses in the panel during the test. A maximum of 10-kip load was applied on one of the decks (Figures 12a and 12b) and corresponding deflections and strains were measured on both decks. Only a limited number of fatigue load cycles were applied on one of the interlocked joints.

Figure 4.12 (a): 3-point static testing on interlocked GFRP deck system (Elevation View)

Figure 4.12 (b): 3-point static testing for interlocked GFRP deck system (Top View)

Chapter 5 focuses on the data analysis and theoretical comparisons of the FRP pedestrian bridge decks evaluated and field implemented in this research.

5. Data Analysis and Theoretical Comparisons

5.1 Introduction

This chapter focuses on the analysis of the data obtained from the tests conducted on the FRP deck systems and the bending behavior under cyclic load including the determination of the deck stiffness. The test results obtained from field testing of the pedestrian bridge and laboratory testing of interlocked decks are also presented.

5.2 Theoretical Calculations and Comparisons

Static tests were conducted on the GFRP (Glass Fiber Reinforced Polymer) decks to determine the stiffness of the decks as explained in Chapter 3. The stiffness values are compared with the values reported by the manufacturer. In addition, vertical deflections at midspan of the deck have been calculated using the stiffness values provided by the manufacturer and compared with the experimental and theoretical deflections.

Equations 5.1 and 5.2 provide the formulae for calculating the stiffness and mid-span deflection, respectively, for an FRP deck system subjected to three-point loading. Equations 3 and 4 provide the formulae for calculating stiffness and mid-span deflection, respectively, for an FRP deck system under four-point loading.

$$E \text{ (at midspan)} = \frac{\left(\frac{W}{\Delta}\right) L^3}{48 I_M} \quad \text{Equation (5.1)}$$

$$\Delta_{max} = \frac{W L^3}{48 E_M I_M} \quad \text{Equation (5.2)}$$

$$E \text{ (at midspan)} = \frac{a * \left(\frac{W}{\Delta}\right) * (3L^2 - 4a^2)}{48 * I_M} \quad \text{Equation (5.3)}$$

$$\Delta_{max} = \frac{a * W * (3L^2 - 4a^2)}{48 * I_M * E_M} \quad \text{Equation (5.4)}$$

Where, E is the stiffness of deck

W is the load applied at midspan

L is the span of the deck

I_M is the moment of inertia reported by the manufacturer.

Δ is the deflection obtained from the experimental results.

E_M is the stiffness of deck reported by the manufacturer.

The stiffnesses determined for the Decks#1 and #2 under three-point and four-point loading configuration were calculated with varying spans of 6ft, 8ft and 11ft while a span of 7ft was used for the Deck#3 under 3-point loading system. The stiffness values calculated from the experimental results are compared with the values reported by the manufacturer in Table 5.1 and presented in Figure 5.1. It has been observed that the stiffness calculated from experimental results for Decks #1, #2 and #3 are within 3% of the stiffness values reported by the manufacturer. Similarly, experimentally observed deflections for Decks #1 and #2 subjected to three-point and four-point loading systems with varying spans of 6ft, 8ft and 11ft and for the Deck#3 under three-point loading system with a span of 7 ft are compared with theoretically calculated values and are tabulated in Table 5.2.

Table 5.1: Comparison of E value

Specimen	Loading	Length (ft)	E Value (Provided) (MSI)	E Value (Calculated) (MSI)	% Difference
Deck#1	3-point	6	3.5	3.3976	2.93%
Deck#1	3-point	8	3.5	3.4	2.86%
Deck#1	3-point	11	3.5	3.3983	2.91%
Deck#1	4-point	6	3.5	3.4292	2.02%
Deck#1	4-point	8	3.5	3.4175	2.36%
Deck#1	4-point	11	3.5	3.4196	2.30%
Deck#2	3-point	6	3.5	3.4362	1.82%
Deck#2	3-point	8	3.5	3.4374	1.79%
Deck#2	3-point	11	3.5	3.453	1.34%
Deck#2	4-point	6	3.5	3.4689	0.89%
Deck#2	4-point	8	3.5	3.4659	0.97%
Deck#2	4-point	11	3.5	3.44	1.71%
Deck#3	3-point	7	3.5	3.48	0.57%

Figure 5.1 describes the validation of stiffness calculation with comparison of stiffness value calculated for Deck#1, Deck#2 & Deck#3 against value reported by manufacturer.

Figure 5.1: Validation of Stiffness Calculation for GFRP Deck

It has been observed from Table 5.2 that the maximum vertical deflections obtained from the experimental results for Decks #1, #2 and #3 are within 4 % of the values obtained from theoretical calculations.

Table 5.2: Maximum deflection value comparison

Specimen	Loading	Length (ft)	$\Delta_{\max}$ (Theoretical) (inches)	$\Delta_{\max}$ (Experimental) (inches)	% Difference
Deck#1	3-point	6	0.7172	0.7426	-3.54%
Deck#1	3-point	8	1.2782	1.3248	-3.65%
Deck#1	3-point	11	2.409	2.47	-2.53%
Deck#1	4-point	6	0.9164	0.9453	-3.15%
Deck#1	4-point	8	1.6332	1.6737	-2.48%
Deck#1	4-point	11	3.0712	3.0284	1.39%
Deck#2	3-point	6	0.7172	0.732	-2.06%
Deck#2	3-point	8	1.2782	1.3038	-2.00%
Deck#2	3-point	11	2.409	2.39	0.79%
Deck#2	4-point	6	0.9164	0.9227	-0.69%
Deck#2	4-point	8	1.6332	1.6437	-0.64%
Deck#2	4-point	11	3.0712	3.0451	0.85%
Deck#3	3-point	7	1.233	1.240	0.52%

The load-deflection curves were plotted to study the response and behavior of the GFRP decks under three-point and four-point loading configurations. The load-deflection plots for all the specimens have shown similar trends. Figure 5.2 shows the vertical deflections of Deck#1 with a span of 11ft under three-point bending. Figure 5.3 shows the vertical deflections of Deck#2 having a span of 8ft under four-point bending. Figure 5.4 shows the vertical deflection of Deck#3 with a span of 7ft under three-point bending.

Figure 5.2: Load-Deflection Plot for Deck#1 at 11ft span length and 3-point bending test

Figure 5.3 shows the behavior of vertical deflection on Deck#2 at 8ft span length with 4-point bending.

Figure 5.3: Load-Deflection Plot for Deck#1 at 8ft span length and 4-point bending test

Figure 5.4 shows behavior of vertical deflection on Deck#3 at 7ft span length with 3-point bending.

Figure 5.4: Load-Deflection Plot for Deck#3 at 7ft span length and 3-point bending test

The linear-elastic responses were observed from Figures 5.2 through 5.4 for the entire duration of loading. This is the typical behavior of the GFRP and this continuous linear-elastic behavior during the full range of loading indicates no damage to the deck until the maximum loads applied during the testing. Any intermediate damage would have resulted in a shift in the load-deflection

response, which did not occur. Furthermore, no visible damage was observed during various test configurations having different spans. These panels can support a load close to their failure point and return to their original shape once the load is removed as observed during failure load tests.

Another important observation from the load-deflection plot is that the transverse stiffness of the deck helped in efficiently carrying the applied loads. Transverse distribution of the applied loads improves the efficiency of the GFRP deck. In comparing the deflections reported by LC and LS, there is relatively small difference between the centerline and panel edge deformations, thus indicating a small amount of transverse curvature of the facesheets (flanges) between the underlying I or W sections.

The measured strain values during the tests also offer valuable insight into the response and behavior of the deck panels. The load-strain plots for all the strains measured at five different locations have been analyzed and typical response of different gauges for Decks#1, #2 and #3 are shown in Figures 5.5 to 5.7 respectively. Figures 5.5 through 5.7 show linear strain patterns that are consistent with the panel deformations, thus providing a linear-elastic response throughout the loading and unloading cycles.

Figure 5.5 (a): Load-Strain Plot for Deck#1 under 3-point bending (notations in Table 3.3)

Figure 5.5 (b): Load-Strain Plot for Deck#1 under 4-point bending (notations in Table 3.3)

Figure 5.6 (a): Load-Strain Plot for Deck#2 under 3-point bending (notations in Table 3.3)

Figure 5.6 (b): Load-Strain Plot for Deck#2 under 4-point bending (notations in Table 3.3)

Figure 5.7: Load-Strain Plot for Deck#3 under 3-point bending (notations in Table 3.4)

Figure 5.5 through Figure 5.7 that, consistent with the panel deformations, the measured strains also responded in a linear-elastic fashion throughout the full range of loading and unloading.

5.2 Behavior of Stiffness under Fatigue

Fatigue is an important factor in the design of bridge structures due to the repetitive nature of applied loads. Fatigue tests were conducted to determine the effect of strain/stress ranges under cyclic loads on the integrity and stiffness of the GFRP decks. During fatigue testing, all the Decks #1, #2 and #3 were subjected to million cycles of loading and the data was collected and analyzed at regular load intervals. During fatigue testing, the panels were visually inspected for any signs of damage or distress, and then static load testing was performed on the deck specimens at specified intervals. None of the panels failed or even showed any visible signs of distress under the fatigue loading.

Table 5.3: Summary of Fatigue Tests

Specimen	Span Length (L)	Load Range		Strain Range		Cycles
		Minimum (W_{max})	Maximum (W_{min})	ϵ_{min} (μ strain)	ϵ_{max} (μ strain)	
Deck#1	8ft	10 kip	20kip	2189	4468	1 Million
Deck#2	11ft	7.5 kip	15 kip	1919	4045	1 Million
Deck#3	7 ft	0.5 kip	1 kip	1176	2227	1 Million

Table 5.3 shows summary of the two-fatigue test used in this study. Figure 5.8 shows the effect of cyclic loading on vertical deflection of Decks #1, #2 and #3 respectively. Figure 5.9 shows change in relative stiffness with the increase in load cycles.

Figure 5.8 (a): Effect of cyclic load on deflection in Deck#1

Figure 5.8 (b): Effect of cyclic load on deflection in Deck#2

Figure 5.8 (c): Effect of cyclic load on deflection in Deck#3

Figure 5.9 provides relative stiffness value as load cycle number increases.

Figure 5.9: Effect of cyclic loading on Relative Stiffness of GFRP Material

It is observed from Figure 5.9 that the vertical deflections in GFRP Decks #1, #2 and #3 remain practically unchanged even after being subjected to million cycles of loading. Thus, Decks #1, #2 and #3 exhibited very good fatigue response.

5.3 Analysis of Field Data

As mentioned in Chapter 4, tests were conducted on the field installed GFRP decks with 100 psf loads. Details of the instrumentation used for measurement are presented in section 4.2. The strain and deflection of the interlocked decks designated as Deck#A and Deck#B were measured. The load is uniformly distributed over the span of a single deck panel to provide a maximum load of 100 psf as per AISC SEI-17 in increments of 25 psf.

The deflection data obtained from the field was compared with the theoretical deflection of the Deck. Figure 5.10 shows a schematic of a field installed deck panel with an overhang on each side of the panel with a uniformly distributed load application.

Figure 5.10: Schematic of an equally overhanging beam with uniformly distributed load

The deflection at any point x along the span length L for equally overhanging beam with uniformly distributed load of W_0 is given by,

$$\text{Deflection} = \frac{\frac{1}{8}W_0(L+2a)Lx^2 - \frac{1}{24}W_0x^4 - \frac{1}{16}W_0(L+2a)^2x^2 + \frac{1}{384}W_0(24a^2 - 5L^2)L^2}{EI_M}$$

Equation (5.5)

Where, E is stiffness of deck provided by manufacturer

W_0 is Uniformly Distributed Load

L is deck span length

I_M is moment of inertial reported by manufacturer

x is distance from midspan

a is overhang length

For calculating deflections at a given location $x=21$ " from the midspan of the pedestrian bridge deck panel the following additional parameters were used:

span length "L" = 90 inch

overhang length "a" = 14 inch

moment of inertia " I_M " reported by manufacturer = 82 in⁴

Stiffness "E" reported by manufacturer = 3.5 Msi

The theoretical deflection values (D1) at location x were calculated for various uniformly distributed loads of 25 psf, 50 psf, 125 psf & 100 psf. The theoretical values were compared with the experimental values obtained in field testing for respective loads as shown in Table 5.4. From Table 5.4, it can be observed that the experimentally measured deflection at $x=21$ " shows a good correlation with the theoretical deflections. The maximum difference in the experimental and theoretical value is within 6.4% at 75% rated load and this difference is well within the acceptable limits. Table 5.5 shows the deflection data obtained from field testing.

Table 5.4: Comparison of experimental and theoretical deflection for Field Testing of Pedestrian Bridge

Load (psf)	Deflections			Deflection limits	
	Experimental	Theoretical	Difference	L/800	L/1000
	Inches	Inches	%	Inches	
50	0.008	0.00818	-2.2	0.12	0.096
100	0.017	0.01616	4.9		
150	0.026	0.02434	6.4		
200	0.034	0.03252	4.4		

Table 5.5: Deflection data for Field Testing of Pedestrian Bridge

Load (psf)	Deck#A		Deck#B	
	D1 (in.)	D2 (in.)	D3 (in.)	D4 (in.)
50	0.008	0	0	0
100	0.017	0	0	0
150	0.026	0	0	0
200	0.034	0.017	0.009	0

From table 5.4, we can see that the experimentally measured deflection at D1 shows a good agreement with theoretical deflections calculated. Thus, we have successfully validated the deflection data obtained in field testing. The maximum difference is 6.4% at 75% rated load and this difference is well within the acceptable limit for field testing data as there are practical problem like existence of brace, uneven distribution of load, positioning of LVDT during field test.

After successful validation of one set of deflection data, we will have a look at all deflection data obtained during field testing. Table 5.5 shows the deflection data obtained for field testing measured using LVDT. D1, D2, D3, D4 are the LVDTs placed beneath the Deck #A and Deck #B.

From table 5.5, we can see that, even the deck under loading shows deflection (D1 & D2) there is no deflection measurement (D3 & D4) for adjacent deck- Deck#B till 150 psf of loading. The adjacent deck- Deck#B shows minor deflection value 0.009 inches at maximum rated load of 200 psf. This shows that, GFRP deck used in pedestrian bridge exhibits good structural performance at 100% rated load of 200 psf. The deck has an ability to withstand rated load without significant deflections and forces very low amount of stress on adjacent deck.

The allowable deflection in the beam should not be more than $L/800$ or $L/1000$ (L is the span length). Here in the deck system of 8 ft. span the allowable deflection should be between 0.12 in. to 0.096 in as shown in Table 5.5. Hence the decks are safe in deflections.

5.3 Analysis of Interlocked Deck Panels in the Laboratory

As mentioned in section 4.4 in this thesis, to imitate the bridge scenario, two GFRP decks “Deck#1” and “Deck#2” were interlocked and subjected to static testing with 10 kip of maximum point load applied on Deck#1.

Details about the instrumentation used for measurement of strain and deflection for interlocked deck system is presented in section 4.4. Trends of load vs deflection and load vs strain are discussed below.

Figure 5.11: Load-Deflection Plot for the Interlocked Deck System (notations in Table 4.2)

Figure 5.12: Load-Strain Plot for Interlocked Deck System (notations in Table 4.2)

From Figure 5.11 & 5.12, it can be seen that both the deflection and strain responses of interlocked deck systems are consistent with each other in terms of linear-elastic behavior in under full range of loading and unloading. The behavior is similar as compared to the responses recorded during individual testing of Deck#1 and Deck#2. Both deflection and strain values return to zero when the applied load is removed which indicates that there is no permanent damage or deformation for the applied load range. The deflection data at specific loads of interest for the interlocked deck system is shown in Table 5.6.

Table 5.6: Deflection data for Interlocked deck system

Applied Load (lb.)	Deck#1				Deck#2
	L1 (in.)	L2 (in.)	L3 (in.)	L4 (in.)	L5 (in.)
200	0.008	0.008	0.01	0.006	0.002
400	0.017	0.017	0.02	0.012	0.006
600	0.027	0.026	0.029	0.017	0.009
800	0.039	0.037	0.041	0.024	0.015
10000	0.526	0.439	0.396	0.271	0.215

5.4 Failure Analysis

As discussed in section 3.4, the deck #1 and deck #3 were tested up to their failure loads. The central point loads at which Deck #1 and Deck #3 failed were 32 kip and 6.4 kip, respectively. This failure load in deck #1 was about 40 times more than the UDL for which it was designed for (100 psf of distributed load corresponding to a 800 lbs. of point load from equal moment considerations). Similarly, in Deck #3, the failure load was 18 times more than the UDL load for which it was designed for (100 psf of UDL or 350 lb. of corresponding concentrated load from equal moment considerations). However, the deck panels were also required to carry a standalone concentrated load of 4000 lbs per foot width perpendicular to the panel (Deck#1 and Deck#2) and 2000 lbs per foot width for the panel (Deck#3). From a standalone concentrated load point of view, the decks have 8 times (Deck #1) and 3.75 times (Deck #3), respectively.

In Deck #1 subjected to the failure load, the deck showed an initial outward movement/buckling at mid span in the outer legs (C-sections), followed by delamination at the flange/web junctions

of the outer legs. Bottom tensile portions the flanges of the inner I-sections experienced rupturing as shown in Figure 5.12.

The failure load on the deck was applied in few cycles. After each cycle, the load was increased gradually to a higher level than the previous cycle. The tensile strains in Deck #1 at failure were near about 10,000 micro strains and around 8600 micro strains in compression. Generally, the GFRP decks fail around 8000-12,000 micro strains. Shear strains at the failure were about 1000 micro strains and there was no failure in the top facesheet under compression. The maximum deflection experienced by Deck#1 was around 5 in.

Figure 5.13 Failure location in Deck #1

The behavior of the deck can be seen by the load- strain curves in Figure 5.13.

Figure 5.14 Load vs Strain curve under failure loading of Deck #1 (notations in Table 3.3)

The failure load on the deck #3 was applied in few cycles. After each cycle, the load was increased gradually to a higher level than the previous cycle. The tensile strains in Deck #3 at failure were near about 14,000 micro strains and around 7300 micro strains in compression. Shear strains at the failure were about 1100 micro strains and there was no failure in the top facesheet under compression.

In deck #3, under the failure load, the deck showed local failures at the bottom of webs, which started in the outer legs and later occurred in the inner legs. The cracks were in the mid span as shown in Figure 5.14. However, the deck did not completely split in to two parts. After the local failures, it returned to its original position once the load was removed. It shows that the deck has good shape memory even after the failure.

**Figure 5.15 Failure in webs/flanges at mid span
Deck #3**

Figure 5.16. Load vs Strain curve under failure loading of Deck #3 (notations in Table 3.4)

The behavior of the beam under failure can be seen in the load vs. strain curves in Figure 5.15. The maximum deflection observed in Deck#3 was 8 in. It can be observed from the curve that the deck consists of good shape memory to return to its initial position.

5.5 Buckling Consideration

Buckling load (P_{cr}) of webs were analyzed for both the deck panels considering a unit length of 12 in. along the panel span with respective web thicknesses using the Euler's buckling equation (Equation 5.6):

$$P_{cr} = \frac{\pi^2 E I}{k L_e^2} \quad \text{Equation (5.6)}$$

Where, E is the stiffness of the web;

I is the minimum moment of Inertia of the web acting as a column;

$I_x = bd^3/12$ and $I_y = db^3/12$;

L_e is the effective length of the web between the flanges;

k is the column effective length factor (assumed to be 1 in this case).

Using the E and I values of the webs, the buckling loads were found to be well in excess of the anticipated concentrated loads of 2000 lb. and 4000 lb. on deck #3 and deck#1, respectively. If there is no flange-web separation near failure loads, webs of the deck panels will be safe against buckling as seen in Table 5.7.

Table 5.7: Evaluation of Buckling loads in deck#1 and deck#3

Panel	Stiffness (E)	I_y	I_x	b	d	L_e	P_{cr}
	X 10^6 psi	in ⁴	in ⁴	in	in	in	lbs.
Deck#1	3.5	0.05273	54	0.375	12	4	83264
Deck#3	3.5	0.01562	36	0.25	12	2	134799

Buckling strength of the webs for Deck#1 and Deck#3 per unit length of 12 in. along the panel were found to be 83.3 kip and 134.8 kip, respectively (Table 5.7). Each of the FRP deck panels evaluated in this research have 4 and 6 webs respectively, and hence can safely carry the applied concentrated loads against buckling.

The summary and conclusions of this work are summarized in Chapter 6.

6. Summary and Conclusions

6.1 Conclusions

In this research, FRP pedestrian bridge decks were evaluated through static and fatigue tests. The strength and stiffness of the decks were successfully calculated and validated under static and fatigue loads. Following summary and conclusions are drawn from this study.

- 3-point and 4-point static bending tests were performed on the two types of GFRP (Glass Fiber Reinforced Polymer) decks having 5"x24" and 2"x 10½" cross-sections with different span lengths of 6ft, 7 ft, 8ft and 11ft.
- The load-deflection and load-strain curves showed linear responses of the decks under loading. The stiffnesses of the GFRP decks were calculated from the static testing and were within 3% of the manufacturer reported values of 3.5 Msi. Similarly, experimentally obtained vertical deflections were compared with the theoretical values. The experimental and theoretical deflection values showed good agreement with the maximum difference being within 4%. The deflections satisfied the commonly used span/800 and span/1000 criteria for pedestrian bridges.
- Fatigue tests were conducted on the two types of decks up to million cycles. The loading corresponds to an expected annual fatigue cycles of the actual pedestrian bridge which is less than about 10,000 cycles, wherein the bridge is used mainly during the summer season. The stiffness after million cycles of loading practically remained unchanged with the maximum reductions being within 3%.
- Both static and fatigue testing showed the linear-elastic response of the FRP deck systems throughout the full range of loading and unloading for load-deflection and load-strain plots. This behavior is typical for GFRP material and indicates the ability of GFRP deck to support the load very close to their failure and return to its original shape when the load is removed without permanent residual deformations.
- The GFRP deck panels of the field installed pedestrian bridge was also subjected to their 100% rated load of 100 psf using sandbags. The deflections values were successfully validated with theoretically calculated deflections. The deck panels also satisfied the

allowable deflection criteria of span/800 and span/1000. The deck panels have an ability to withstand the rated loads without significant deflections and loads including the load-transfer on the adjacent deck panels due to the mechanical interlock.

- Based on all the experimentation and data analysis, we can conclude that, both types of GFRP decks (24"x5" and 10¼"x2") have excellent strength and stiffness values under static and fatigue loads. As per the design live loads, the decks are well suited for pedestrian bridge applications. The deck panels exhibited 3.75 to 8 times the reserve capacity for point loads of 2000 lb. over a unit foot width of the panels and 18 to 29 times the reserve capacity for a UDL of 100 psf.
- GFRP decks with larger cross-section of (24"x5") were selected for field implementation vs. the smaller cross-section of (10.25"x2") based on the end-user considerations, though both the deck types satisfy the strength and serviceability criteria.

6.2 Recommendations for Future Work

Following recommendations are made for conducting future research and field implementation.

- Optimization of GFRP decks with different web and flange configurations in terms of fiber/fabric configurations, geometry, and failure modes for enhancing the bending moment and increasing the load capacities.
- Repair and evaluation of GFRP decks with local failures using appropriate fiber/fabric and resin systems.

7. References

- [1] U.S. Government Accountability Office. Report to Congressional Committees: Highway Bridges—Linking Funding to Conditions May Help Demonstrate Impact of Federal Investment. September 2016.
- [2] Shekar, Vimala, "Effect of fiber architecture on properties of pultruded composites" (2007). *Graduate Theses, Dissertations, and Problem Reports*. 1811. <https://researchrepository.wvu.edu/etd/1811>
- [3] L.C. Hollaway, A review of the present and future utilization of FRP composites in the civil infrastructure with reference to their important in-service properties, *Construction and Building Materials*, Volume 24, Issue 12, 2010, Pages 2419-2445, ISSN 0950-0618, <https://doi.org/10.1016/j.conbuildmat.2010.04.062>.
- [4] C. E. Bakis and Lawrence C. Bank and V. L. Brown and E. Cosenza and J. F. Davalos and J. J. Lesko and A. Machida and S. H. Rizkalla and T. C. Triantafillou, *Journal of Composites for Construction*, vol6-2,76-87, 2002 <https://ascelibrary.org/doi/abs/10.1061>
- [5] Mohsen Heshmati, Reza Haghani, Mohammad Al-Emrani, Environmental durability of adhesively bonded FRP/steel joints in civil engineering applications: State of the art, *Composites Part B: Engineering*, Volume 81, 2015, Pages 259-275, ISSN 1359-8368, <https://doi.org/10.1016/j.compositesb.2015.07.014>.
- [6] Libo Yan, Bohumil Kasal, Liang Huang, A review of recent research on the use of cellulosic fibers, their fiber fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering, *Composites Part B: Engineering*, Volume 92, 2016, Pages 94-132, ISSN 1359-8368, <https://doi.org/10.1016/j.compositesb.2016.02.002>.
- [7] Keller, T., & Bai, Y. (2010). Structural Performance of FRP Composites in Fire. *Advances in Structural Engineering*, 13(5), 793–804. <https://doi.org/10.1260/1369-4332.13.5.793>
- [8] Fang H, Bai Y, Liu W, Qi Y, Wang J, Connections and structural applications of fiber reinforced polymer composites for civil infrastructure in aggressive environments, *Composites Part B* (2018), doi: <https://doi.org/10.1016/j.compositesb.2018.11.047>.

- [9] Xiao Yang, Yu Bai, Faxing Ding, Structural performance of a large-scale space frame assembled using pultruded GFRP composites, *Composite Structures*, Volume 133, 2015, Pages 986-996, ISSN 0263-8223, <https://doi.org/10.1016/j.compstruct.2015.07.120>.
- [10] Xiao Yang, Yu Bai, Fu Jia Luo, Xiao-Ling Zhao, Faxing Ding, Dynamic and fatigue performances of a large-scale space frame assembled using pultruded GFRP composites, *Composite Structures*, Volume 138, 2016, Pages 227-236, ISSN 0263-8223, <https://doi.org/10.1016/j.compstruct.2015.11.064>.
- [11] Dian Zhu, Huiyuan Shi, Hai Fang, Weiqing Liu, Yujun Qi, Yu Bai, Fiber reinforced composites sandwich panels with web reinforced wood core for building floor applications, *Composites Part B: Engineering*, Volume 150, 2018, Pages 196-211, ISSN 1359-8368, <https://doi.org/10.1016/j.compositesb.2018.05.048>.
- [12] Zafari, Behrouz & Mottram, James. (2015). Characterization by Full-Size Testing of Pultruded Frame Joints for the Startlink House. *Journal of Composites for Construction*. 19. 04014033. 10.1061/(ASCE)CC.1943-5614.0000488.
- [13] Ahmed Godat, Frédéric Légeron, Vincent Gagné, Benjamin Marmion, Use of FRP pultruded members for electricity transmission towers, *Composite Structures*, Volume 105, 2013, Pages 408-421, ISSN 0263-8223, <https://doi.org/10.1016/j.compstruct.2013.05.025>.
- [14] Ernesto Guades, Thiru Aravinthan, Mainul Islam, Allan Manalo, A review on the driving performance of FRP composite piles, *Composite Structures*, Volume 94, Issue 6, 2012, Pages 1932-1942, ISSN 0263-8223, <https://doi.org/10.1016/j.compstruct.2012.02.004>.
- [15] Hastak, M., D. W. Halpin, and T. Hong. Constructability, Maintainability, and Operability of Fiber Reinforced Polymer (FRP) Bridge Deck Panels. Publication FHWA/IN/JTRP-2004/15. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2004. doi: 10.5703/1288284313163.
- [16] Bank, Lawrence. (2006). Application of FRP Composites to Bridges in the USA. Japan Society of Civil Engineers (JSCE), Proceedings of the International Colloquium on Application of FRP to Bridges, January 20. 9-16.

- [17] Creative Pultrusions (Website: <https://www.creativepultrusions.com/>)
- [18] GangaRao, H., Taly, N., Vijay, P. (2006). Reinforced Concrete Design with FRP Composites. Boca Raton: CRC Press, <https://doi.org/10.1201/9781420020199>
- [19] Shaikhon, Omar. (2012). "Polymers and Their Use in Construction" 10.13140/ RG. 2.2.24201. 75366.
- [20] Wallenberger, F.T and Bingham, P.A., ed., Fiberglass and Glass Technology, Energy-Friendly Compositions and Applications, Springer, New York, 2010.