NIST Special Publication 1244

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David Goodwin*
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Jazalyn Dukes
Jae Hyun Kim
Chiara Ferraris
Li-Piin Sung
Materials and Structural System Division
Engineering Laboratory
National Institute of Standards and Technology
**Authors contributed equally to this report*

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December 2019

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Under Secretary of Commerce for Standards and Technology

National Institute of Standards and Technology Special Publication 1244
Natl. Inst. Stand. Technol. Spec. Publ. 1244, 116 pages (December 2019)
CODEN: NSPUE2

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1244

Acknowledgements

NIST acknowledges the extensive input and support of the following subject matter experts: James Jirsa, Bret Lizundia, William Gold, Charles Bakis, and John Myers. Their contributions, diversity of perspectives, critical input, and help facilitating the workshop are much appreciated. Workshop participants are thanked for their valuable feedback and input on the research needs for FR composite retrofitted building performance. NIST also thanks Ravi Kanitkar, Bret Lizundia, Jovan Tatar, and Charles Bakis for assistance in editing this report. Their time and efforts are greatly appreciated. Lastly, the authors gratefully acknowledge Jeffery Bullard, Stephanie Watson, Steven McCabe, and Ken Snyder for their advice and suggestions during the workshop and assembly of this report.

Abstract

Throughout the United States, the use of fiber reinforced (FR) composites in building and infrastructure applications has been steadily on the rise. FR composite materials, which include fiber reinforced polymer (FRP) composites and fiber reinforced cementitious matrix (FRCM) composites, are used to repair, strengthen, and seismically retrofit structural components (*e.g.*, columns, beams, walls) of existing buildings and infrastructure. FR composite retrofits have become competitive with more traditional retrofit techniques due to their high strength, light weight, low profile, and corrosion resistance. These FR composite properties have resulted in lower overall costs and more efficient, less labor-intensive installation processes. Furthermore, repair, strengthening, and seismic retrofit of aging structures with FR composites leads to improved building and infrastructure resilience. Since the use of FR composites in the civil engineering field has matured, this report serves to review the state-of-the-art for FR composite performance and identify research needs requisite to advancing the field. The report focuses primarily on externally bonded FRP composites since they are most commonly used in practice in the United States. The research needs were obtained by an extensive literature review and from input received at a national stakeholder workshop at NIST in 2018. The findings of this report describe the materials and structural level research needs prioritized per the subject matter expert opinions received at the workshop. Major materials research needs include improvement of inspector certification processes and improvement or development of test methods that assess the condition of FR composites after installation and long-term use. Other major research needs include identification of bond degradation mechanisms between FRP composites and concrete and relation of accelerated conditioning protocols to long-term exposure outdoors. Structural research needs include development of design standards and guidelines for FR retrofitted components and buildings, improvement of inspection practices, structural-scale experimental studies, and improvement of numerical modeling capabilities. This report is intended to inform future research plans developed by various stakeholders concerning the performance of buildings and infrastructure that are retrofitted or repaired with FR composites.

Keywords

FRP, Fiber reinforced composites, External retrofits, Materials, Resilience, Structural performance, Reinforced concrete, Long-term performance, Weathering, Degradation, Bond degradation, Numerical modeling, FRP retrofit design

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Executive Summary

The use of fiber reinforced (FR) composites as retrofits for buildings and infrastructure has steadily increased in the United States. Retrofitting with FR composites has advantages over other traditional retrofit schemes since FR composites have unique characteristics such as their light weight, low profile, corrosion resistance, and ease of installation. Although, FR composite retrofits have been the topic of research for the past two decades, there are still knowledge gaps that need to be addressed to improve the state of practice.

This report identifies the research needs concerning FR composite retrofits both at the material and structural levels. The research needs cover a broad range of issues including material selection, initial- and long-term performance of FR composite retrofitted structures, material degradation, and design considerations and standards. The research needs are identified primarily based on the feedback received at a national workshop of subject matter experts hosted by NIST in May 2018. The workshop brought together stakeholders from FR composite manufacturers, design firms, academia, standards developing organizations, and government to identify current research needs that will help improve understanding of structural performance involving FR composite retrofits. A thorough literature review, used to organize the research needs discussed at the workshop, is also included in this report. The report focuses primarily on externally bonded fiber reinforced polymer (FRP) composites since they are the most commonly used in the United States.

Research needs are grouped based on whether they are at the materials level or the structural level. The research needs are prioritized based on the input received at the national workshop into three categories: Highest, Higher, and High. Research needs were prioritized to help inform development of future research plans with a high impact on the state-of-practice. At the materials level, the Highest priority research needs include: improving inspector certification processes and inspection protocols, improving test methods such as pull-off tests and tensile tests to reduce the associated inherent uncertainty, developing new test methods, identifying bond degradation mechanisms between FRP composites and concrete, improving accelerated conditioning protocols that simulate outdoor degradation, developing metrology for fire rating of FR composites, investigating FRP composite application to non-concrete substrates, and assessing correlations between small- and structural-scale tests. The Highest priority structural research needs include:

developing design standards and guidelines for FR composite retrofitted structures, conducting experimental research on FR composite retrofitted structural components, conducting structural-scale testing on retrofitted structures, developing and validating models capable of simulating aging and accumulation of damage, and improving inspection practice.

The research needs outlined in this report are aimed to inform the diverse research plans developed by stakeholders including NIST, government agencies, universities, private companies, and other organizations, concerning the use of FR composites for repair and retrofit of buildings and infrastructure. Further investigation of the outlined research needs by stakeholders will ultimately help develop and enhance FR composite performance and the state-of-practice for our nation's building and infrastructure envelope.

1. Introduction

1.1. Motivation of Research

The resilience of infrastructure is often improved using fiber reinforced polymer (FRP) composites and fiber reinforced fabric cementitious matrix (FRCM) composites. Application of externally bonded FRP and FRCM composites onto structures can help repair structural components deteriorated due to degradation or an excessive loading event. Building components can be retrofitted for increased seismic and gravity loads. Compared with traditional reinforcement materials, fiber reinforced (FR) composites are light weight and flexible for ease of application, low profile additions to existing structures, and corrosion-resistant. These unique characteristics make FR composites a desirable retrofit material for existing buildings. The cost of FR composite material use is generally lower due to decreased transportation and installation costs. For example, one article stated that FRP composites used in place of steel retrofits can decrease the overall cost of retrofitting by 17.5 % to 30 % in civil engineering applications [1]. FR composites may also improve the practicality of gradual repair to the nation's aging infrastructure with rapid installation times, ease of application to many different types of building components, and ability to increase a structure's lifetime until full replacement of the structure. FR composites can improve structural performance and even save lives by preventing infrastructure failure.

This report primarily focuses on FRP composites attached externally to concrete since this is the most common way in which FR composites are currently applied to structures in the US. Since the FRCM market is also growing in the US, this type of material is also discussed briefly throughout the report. This report acknowledges that the use of FRP composites as internal reinforcement of concrete is also becoming more widespread across the US and has some research needs similar to externally bonded FRP composites [2]. However, internal FRP reinforcement used in buildings and infrastructure present some unique challenges that require identification of research needs specific to this application.

FR composites are being widely used in highway structures (*e.g.*, bridges, overpasses) across the US as reported by the National Cooperative Highway Research Program (NCHRP), which assessed the current practice of incorporating FR composites into highway structures across the

US [3]. FR composites are also being used in buildings to repair and retrofit structural components including shear walls, columns, beams, and slabs. The U.S. FRP composite market was valued at $21.38 billion in 2016 with approximately one-third of this market represented by the construction industry [4, 5]. As a whole, the U.S. demand for FRP composites will rise at an annual rate of 11.3 % by 2025 with the construction market advancing at the most rapid rate [4, 5].

The American Concrete Institute (ACI) [6, 7], the International Code Council Evaluation Service, Inc. (ICC) [8, 9], the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB) as part of the National Cooperative Highway Research Program (NCHRP) [3, 10-13], several state departments of transportation (DoT) [14-16], and academia, (*e.g.*, [17, 18]), acknowledge that FR composites have been used in a wide variety of projects, but some documents from these organizations indicate that more extensive understanding of their initial and long-term performance are needed [6-10]. Earlier reports by the National Institute of Standards and Technology (NIST) indicated that FRP composite use has matured greatly in other markets such as the automotive, marine, and aerospace sectors [20, 21]. For building and infrastructure applications, further research and testing methods are needed due to differences in material, processing, loading, and environment associated with the use of FRP composites in civil engineering in comparison with applications such as aerospace and automotive [20, 21]. The NCHRP recommended that guidelines, commentary, and examples are needed for design, construction, and maintenance of FRP composites before the material can fully mature and proliferate [13]. A more recent NIST report documented a meeting among stakeholders dedicated to overcoming barriers to adoption of composites in sustainable infrastructure and determined that durability testing, design data clearinghouse, and education and training were needed [22].

This report reviews the state-of-the-science and practice to identify the future research needs required to assess and improve the performance of FR composites used in buildings and infrastructure with a focus on linking material level performance to structural level performance.

1.2. Scope

Currently, a general lack of data and test methods to assess the health and performance of FR composite materials in laboratory and outdoor environments is a major barrier to determining their usable lifetime. An evaluation of performance and health of FR composites in actual structural components requires further investigation to inform stakeholders and to make progress on developing new test methods and improving existing test methods, test data, numerical modeling capabilities, and design standards and guidelines.

This report will seek to develop a roadmap that prioritizes the current research needs for FR composites used in repair and retrofit of structures with externally bonded FR composites. Note that in this report the "retrofit" terminology includes both strengthening for gravity loads and seismic retrofit of structural components. The report is primarily focused on FRP composites because of the widespread use of this product in the U.S. FRCM composites are also described since they are increasingly being used in the US, albeit not as readily as FRP composites. This report provides a state-of-the-science review on FR composites used in indoor and outdoor structural applications. The report details the future research that is needed to improve the resilience of structures retrofitted with FR composites from the material level all the way to the structural level. The research needs are identified based on the input received at the workshop of national experts held at NIST in May 2018 as well as a comprehensive literature review.

1.3. Development and Structure of the Report

The report is based on 1) a comprehensive literature review conducted to identify research needs, and 2) feedback received from a broad range of stakeholders at a workshop hosted by NIST on May 15, 2018.

1.3.1. Identification of Research Topics

The report is structured around two major research topics; each research topic is divided into three or four subtopics. The first topic is on research related to FR composite materials attached to substrates. The subtopics within this research topic include material selection, initial and long-term performance of FR composites, and challenges in usage of this material. The second research topic is related to the performance of individual structural components as well as the entire structure retrofitted with FR composites in response to external loadings and environmental impacts. This research topic discusses the initial and long-term performance of retrofitted structures and the required improvements in design and standards concerning usage of FR composites. The topics and subtopics were identified based on a comprehensive literature review and they cover a broad range of research and implementation activities required to improve the performance of FR composite retrofitted structures both at the material and structural level. Appendix A summarizes the main research needs identified at the stakeholder workshop.

1.3.2. Stakeholder Workshop

A stakeholder workshop was conducted on May 15, 2018, at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD (see Appendix B). The workshop provided input from a broad range of stakeholders through facilitated discussions of the two major topics. Participants came from federal agencies, academia, standard developing organizations (SDOs), professional organizations, and engineering firms (see Appendix C). The workshop participants identified research needs concerning each of the research topics and subtopics, discussed above, through facilitated discussion in three concurrent breakout sessions for each topic. In order to prioritize the research needs, participants were asked to vote on the research needs identified in each breakout session. Each participant was given six votes and could assign up to two votes to the topics of highest research priority. Note that voting at the workshop was limited by the background and experience of the workshop participants (Appendix C).

Based on the number of votes received for each research topic, the research needs were grouped into three priority groups: Highest, Higher, and High. Three priority groups were determined since the number of votes received for each research need clustered into one of three distinct vote number groups. The assigned priority group for each research topic can be found in Chapter 3, Chapter 4, and Appendix A.

1.3.3. Organization of the Report

Chapter 1 describes the motivation and scope of the report as well as the information related to the development and structure of the report. Chapter 2 describes background information on FR composites and state-of-the-art in research and practice concerning the use of FR composites in retrofitting structures. In addition, this chapter outlines the research gaps identified in the literature both at the materials and structural level. Chapter 3 discusses the research needs identified at the workshop concerning the performance of FR composite materials. Chapter 4 outlines the research needs identified at the workshop concerning the performance of FR composite retrofitted structures. Chapter 5 provides a summary of the literature research needs, which were used to organize the workshop, as well as the prioritized research needs identified by stakeholders at the workshop. Literature research needs not discussed at the workshop are also discussed in Chapter 5.

2. State-of-the-art of FR Composite Retrofitted Buildings and Infrastructure

2.1. Overview

Chapter 2 provides comprehensive background on FR composites and their use in buildings and infrastructure. Specific research needs identified in the literature are also discussed throughout this chapter. Background is provided on FRP composites, including fiber types and properties, polymer types and properties, fiber arrangement types and the form of FRP composites applied in practice, FRP anchors, mechanical fasteners used for FRP composite attachment, as well as background on FRCM composites. The chapter highlights the types of FR composite applications and their benefits for structural retrofit or repair, an overview of the intended lifetime of FR composite repairs/retrofits, and degradation mechanisms for FR composite materials and interfaces. Also included are materials characterization methods used to assess the performance of FRP composite systems at three different scales, which include standalone FRP composites, FRP assemblies (FRP composite + substrate), and FRP retrofitted structures. At each scale, materials characterization methods are organized by initial and long-term performance. In the FRP assembly section, inspection methods, destructive and non-destructive methods used in the field, and laboratory studies are described for initial and long-term performance. In the FRP retrofitted structures section, experimental studies (which include both field and laboratory studies) and numerical studies are provided for initial and long-term performance.

2.2. Background on FR Composites

FR composites are high-strength materials that have been used for some time in the aerospace, marine, and automotive industries. Lately, there has been a large increase in FRP composite use in civil engineering applications to repair and retrofit existing structures, particularly concrete and masonry buildings and bridges [23, 24]. FR composites (FRP composites specifically) have been used in infrastructure applications to repair and retrofit new support structures, build light weight bridge decks, and provide corrosion-resistant internal reinforcement [12, 18, 23, 25, 26]. FR composites have several advantages over traditional reinforcement/strengthening materials which include high load capacities, light weight, and corrosion resistance. In addition to these advantages, the ease of FR composite application, which reduces construction costs and time, makes FR composites a preferred material. FR composites consist of polymer or cementitious matrices containing fibers for reinforcement. FR composites include fiber reinforced polymers (FRP) composites and fiber reinforced cementitious matrix (FRCM) composites. Fiber reinforcements can be arranged in many different ways when embedded in a polymer or cementitious matrix and the resulting FR composite can be applied to a structure in several different forms [7].

2.2.1. Fiber Types, Polymer types

2.2.1.1. Fiber Types

The three most common types of fibers used in infrastructure composites are carbon, glass, and aramid, each of which is described below. All fibers have high strength (> 2 GPa) and low ductility (failure strain below 2.6 %) which are critical characteristics for strengthening and repair applications. The low ductility of FRP composites usually does not have an effect on the overall stiffness of the building system level response since FRP composites are applied locally to structural components. A comparison of the properties of each fiber type is shown in Table 2.1.

<u>*Carbon* Fibers</u>: Carbon fibers (typically 5 µm to 10 µm in diameter) are high aspect ratio ribbons of graphenic carbon that are oriented parallel to the fiber axis and have high strength and modulus due to folding and interlocking of the ribbons. Carbon fibers have the highest strength and modulus of elasticity (*i.e.,* stiffness) of all three types of fibers described in this section and the lowest failure strain of all three fibers. [27, 28]. Carbon fibers are typically made by graphitizing polyacrylonitrile (PAN) or by extruding pitch, a petroleum or coal tar precursor. Carbon fibers made from PAN are typically higher in strength than pitch-based carbon fibers due to the higher degree of orientation and presence of larger crystallites in the formed fibers [27]. In addition to their high strength and modulus of elasticity, carbon fibers have many other advantages relative to the other two common fibers described here, which include high moisture and chemical resistance, thermal stability, corrosion resistance, and minimal creep rupture and fatigue [28]. Disadvantages of carbon fibers include lower impact resistance and lower failure strain (*i.e.*, less ductile) than the other fibers described in this section. Carbon fibers also have a negative coefficient of thermal expansion (CTE) which can lead to expansion under cold temperatures and generation of internal stresses in a composite [28]. In contrast, the polymer matrix of an FRP composite can have a positive CTE,

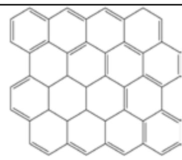
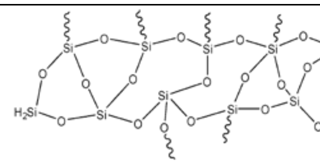
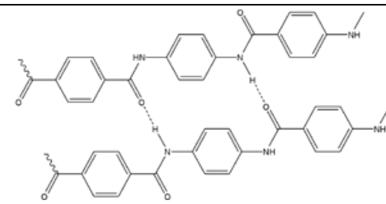
so FRP composites can be tailored to have a CTE closer to zero or to that of the substrate [28]. Carbon fibers do not corrode but are electrochemically different than steel and can form a galvanic couple with surrounding steel that leads to its corrosion [29]. Carbon fibers also have the highest cost compared to glass and aramid fibers [4, 5]. FRP composites manufactured with carbon fibers are often called CFRP (carbon fiber reinforced polymer) composites.

Glass Fibers: Glass fibers are made of silicates, typically in amorphous form for strength, with a small mass fractions of oxides such as boron, calcium, sodium, iron, and aluminum [28]. Several types of glass fibers are used or being developed for civil engineering applications but the most commonly used glass fiber is E-glass which is an alumina-calcium borosilicate glass with less than 1 % (by mass) alkali oxides [28]. Glass fibers are the cheapest type of fiber, have been used in infrastructure applications [30], and are widely used in applications other than infrastructure such as in the automotive and aerospace industries. Glass fibers have lower tensile strengths and moduli of elasticity than carbon fibers, lending themselves to use in applications where lower strength and stiffness are acceptable to achieve a lower cost. Glass fibers also have higher failure strain (*i.e.*, elongation at break) and greater impact resistance than carbon fibers. Unlike carbon fibers, glass fibers do not lead to galvanic corrosion of surrounding metal (Table 2.1) [31]. Thus, glass fibers are often used in place of carbon fibers when contact of the FR composite with metal objects (*e.g.*, bolts, steel connections, *etc.*) will occur. Note that the low modulus of elasticity of glass fibers makes them less useful than carbon fibers on metal structures. However, glass fibers typically serve as galvanic insulation between metal and carbon fibers on metal structures. Disadvantages of glass fibers include short creep lifetime or creep rupture time under high sustained loads, low modulus of elasticity, and low strength. Furthermore, moisture-induced degradation, or hydrolysis, of the glass fiber coating (also called a sizing) that promotes fiber/matrix adhesion, can decrease the adhesion between the glass fibers and the matrix [32, 33]. Stress corrosion, or moisture-induced degradation of fibers while under static fatigue, is another issue in which water molecules can extract cations from glass (*i.e,* leaching) to facilitate hydrolysis reactions (*e.g.,* bond-breaking within glass structure with loss of water) of glass fibers (and glass fiber sizings) often at defect sites/microcracks, causing these defect sites/microcracks to expand [33, 34]. The severity of both moisture-induced degradation mechanisms can be enhanced under both acidic and alkaline conditions (Table 2.1) [34]. FRP composites made with this type of fiber are often called GFRP (glass fiber reinforced polymer) composites.

Aramid Fibers: Aramid fibers are nylon-based fibers (*i.e.*, aromatic polyamides) that have a high strength and flexibility [35]. Unlike the other two types of fibers, aramids are highly impact-resistant because they are non-linear in compression. Aramids also have high strength and modulus. They are higher in cost than glass fibers but are not as expensive as carbon fibers. Although aramids are resistant to chemical attack, they have disadvantages in that they degrade under many environmental conditions (*e.g.*, UV exposure and moisture) and have lower creep rupture times than carbon fibers (Table 2.1) [28, 36, 37]. Aramids have been used as tendons, bars, and cables and are a good alternative to carbon fibers in applications where electrical conductivity is a concern since they are non-conductive and do not lead to corrosion of surrounding metals [38, 39].

Of all three types of fibers, carbon fibers are the most commonly used in infrastructure applications since they have the highest modulus, strength, and ability to carry sustained stress. Glass fibers are also commonly used to save on cost when reduced strength, modulus of elasticity, and creep rupture lifetime are acceptable. A comparison of fiber properties for the three common fiber types are shown in Table 2.1. Many other fibers exist or are being developed in research laboratories but are not as commonly used in infrastructure applications with the exception of basalt fibers, which have recently become more prevalent in the civil engineering field [40]. Basalt fibers are inorganic fibers derived from molten volcanic rock that primarily contain SiO_2 and Al_2O_3 [40, 41]. Basalt fibers can be manufactured at a lower price than glass fibers and carbon fibers and basalt fibers have a higher strength and modulus of elasticity than glass fibers [41]. However, environmental degradation is a disadvantage since hydrolysis of basalt fiber sizings can lead to matrix/fiber debonding which decreases fatigue strength under cyclic loading [40].

Table 2.1 Properties of three common types of fibers [7, 28, 31, 42]

Consideration	**Carbon**	**Glass**	**Aramid**
Chemical structure			
Usable temperature range	Thermally stable up to 1927 °C (3500 °F) in absence of O_2, Thermally stable up to 400 °C (≈ 752 °F) in air	Softens at temperatures over 816 °C (1500 °F)	Melting point >500 °C (932 °F) Stable to > 177 °C (350 °F) in air and absence of O_2
Coefficient of thermal expansion	-0.4×10^{-6} K^{-1}	Similar to concrete (2×10^{-6} K^{-1}), 4.9×10^{-6} K^{-1}	-6×10^{-6} K^{-1}
Tensile strength, Young's modulus, Failure strain	3.4 GPa 230 GPa 1.1 %	2.0 GPa 76 GPa 2.6 %	3.0 GPa 130 GPa 2.3 %
Creep rupture and fatigue	High resistance	Low resistance	Moderate resistance
Impact resistance	Low resistance	Moderate resistance	High resistance
Electrical conductivity	High conductivity	Excellent insulator	Insulator
Environmental Conditions (UV, moisture	Excellent moisture and chemical resistance; Can lead to galvanic corrosion of metals in contact with carbon fibers	Sensitive to moisture under alkaline conditions	Extremely sensitive to UV radiation, moisture; resistant to chemical attack
Alkalinity/ acidity exposure	High resistance	Not tolerant	Not tolerant

2.2.1.2. Polymer Matrices

There are two general categories of polymer matrix used for FRP composites: thermosets and thermoplastics. Thermosets are the main class of polymers used as the FRP composite polymer matrix in building and infrastructure applications. Thermosets are polymers that are prepared from two parts, a resin and a curing agent. Once the two parts are mixed, cross-linking or curing occurs and the solidified thermoset polymer is formed. Thermosets cannot be melted and reformed due to the cross-links formed between polymer chains that prevents the chains from sliding past each other at elevated temperatures. Thermosets are most commonly used for structural applications. For FRP composites, thermoset resins and curing agents are mixed in a liquid state at room temperature prior to curing. The thermosetting resin chemistry is often complex and requires carefully following manufacturer's directions during mixing [6]. The reinforcing fibers are then impregnated with this mixture prior to curing. The curing reaction occurs slowly at ambient temperature and can be accelerated with applied heat. The most commonly used thermoset resin is epoxy and other thermosets are sometimes used:

- Epoxy (most commonly used)
  - Advantages: Least shrinkage of all thermosets described, high moisture and temperature resistance; best mechanical properties of all thermosets described; long working times available.
  - Disadvantages: Generally more expensive than other thermosets; dispersion issues in terms of reaching critical mixing parameters and consistency, corrosive when handling, cure properties are more affected by typical outdoor temperature ranges than polyesters, vinyl esters, and some formulated polyurethanes.
- Polyurethanes
  - Advantages: High temperature and moisture resistance after cure; can be formulated for low temperature cure.
  - Disadvantages: Very susceptible to moisture during cure; high cost; uses isocyanates which can be extreme sensitizers, especially at low molecular weight; stoichiometric addition is critical to performance.
- Polyesters
  - Advantages: Low cost; can be formulated to work at lower temperatures than epoxies; cure efficiency and speed can be adjusted in the field with accelerator concentration.
  - Disadvantages: Shrinks more than epoxy and some vinyl esters during cure leading to more residual stresses between the fiber and matrix, in turn reducing fatigue performance; may be susceptible to saponification; polyesters are often diluted with styrene which creates

volatile organic compounds (VOCs) that are a problem to work with on-site; often uses three-part systems which can be a safety factor if mixed incorrectly; poor acid and chemical resistance due to ester groups.

- Vinyl Esters
    - Advantages: Less shrinkage than polyesters but more shrinkage than epoxy; can be formulated to cure at lower temperatures than epoxies; cure efficiency and speed can be adjusted in the field with accelerator concentration; can be cured with ultraviolet (UV) light.
    - Disadvantages: More expensive than polyesters but less expensive than epoxy; more shrinkage than epoxy; vinyl esters are often diluted with styrene which creates volatile organic compounds (VOCs) that are a problem to work with on-site; often uses three-part systems which can be a safety factor if mixed incorrectly.

Thermoplastics are polymers that are solid at room temperature and can be melted and reformed. In building and infrastructure applications, thermoplastics are rarely used since they cannot be heated and shaped easily around fiber fabrics in the field. Pre-formed thermoplastic materials can be manufactured in the laboratory and used on building and infrastructure. However, thermoset pre-formed jackets for columns and other building components are more common. In a manufacturing facility, thermoplastics can be heated to a liquid state and pressurized to impregnate reinforcing fibers. Then the thermoplastic can be cooled back into a solid while being held under pressure [43]. Thermoplastics are most often prepared with shortened fibers since they can be more easily mixed under high temperature and extruded from the mixer as a composite. Advantages of using thermoplastics include high tensile strain to failure, higher fracture toughness, higher impact strength, recyclability, longer shelf life, and less processing time (but requires more energy to process) [44]. Some common types of thermoplastics used with reinforcing fibers in other industries include polyamides (*e.g.* Nylon), polyether ether ketone (PEEK), and some polyurethanes.

Thermosets are more commonly used in outdoor applications since they are low viscosity and can easily impregnate fabrics at room temperature before cure. In contrast, thermoplastics have relatively high viscosities, even at elevated temperatures, and require pressurization and more sophisticated equipment to impregnate fabrics [43]. Durability is important to consider as polymers can degrade in the presence of UV light, moisture, and temperature. Depending on the application of an FRP composite retrofit, durability should be considered in the design specifications, especially when determining if a specific polymer matrix should be used without a protective coating [7]. Thermosets are generally more thermally stable, moisture resistant, and chemically resistant than most thermoplastics [44].

2.2.2. Types of Fiber Arrangements and Forms of FRP Composites

Several different forms of FRP composite are used to retrofit/strengthen structures with FRP composites. First, it is important to define the different arrangements of fibers used before addition of a polymer matrix, or resin.

Common Fiber Arrangements:

Fabrics or sheets: An arrangement of fibers in two dimensions that can be woven, nonwoven, knitted, or stitched. Multiple layers of fabrics or sheets may be stitched together. A single layer of fabric is called a *ply*. Fabrics or sheets can be unidirectional, multidirectional, or randomly oriented. Chemical binders are often used to hold fibers together in fabrics/sheets and sizings, or coatings, are used to promote compatibility with the saturating resin.

Mats: Randomly oriented fibrous material in two dimensions. Mats can contain long filaments like fabrics but can also include chopped fibers and short fibers. Mats can also be held together by a binder.

Tow: An untwisted bundle of continuous fibers. Also called a strand.

Yarn: A twisted *bundle* of tows/strands.

Common FRP Forms (Resin + Fiber Arrangement):

When a saturating resin is added to a fiber arrangement and cured, an FRP composite is formed. There are several different forms of FRP composites that can be broadly categorized by installation method. The form chosen is largely dependent on the site of application and the mechanical load imparted onto the FRP composite by the structure. The saturating resins used are thermosets, or cross-linking polymers such as epoxy. The final fiber volume in the composite must be considered since it influences the modulus of elasticity.

Primers and putties are often applied to a substrate prior to FRP composite attachment and should be cured and applied according to the FRP manufacturer recommendations [7]. Primers and putties improve the bond between the substrate and the FRP composite and differ from the saturating resin used for the FRP composite as defined below:

Saturating Resin or Saturant: The resin used to impregnate the fiber fabric prior to application. The saturating resin is also applied to the concrete substrate prior to attachment of the saturated fiber fabric [7].

Primer: Primers are low-viscosity resins used to penetrate into the substrate surface and improve the bond between the FRP composite and the substrate.

Putty: Putty is a thickened paste, typically prepared by addition of sand or fumed silica to a resin [7]. The resin is either the same as the saturating resin or is a resin that is compatible with the saturating resin. Putties are applied to fill substrate voids and smooth areas of the substrate surface [7]. Putties can also be used to seal the outer edges of saturated FRP fabrics.

Adhesives: Throughout the report, the adhesive is defined as the material between the saturated fabric and the substrate. It is typically the saturating resin but can be a different resin and include the primer and putty [7].

The substrate, typically concrete or masonry, should be in sound condition prior to application of primer, putty, and FRP composites. Substrate repairs and preparation may be necessary: repairs can include removal of unsound concrete, surface preparation to achieve a specified surface profile, rounding of corners, crack repair, drying of the concrete, or corrosion repair of exposed rebar [7, 45].

After any needed repair or preparation of the substrate, primer, putty, and/or saturating resin can be added to the substrate according to manufacturer specifications. The environmental conditions at the time of application must be considered [7].

Of the following three types of FRP composite forms, the first two are most common [35]:

Wet layup systems: The unidirectional or multidirectional fiber sheets (or fabrics) are saturated with resin manually or with a machine, on-site before and/or during attachment of the saturated fabric to the substrate [7]. The saturated fabrics cure in place which leads to adhesion of the formed FRP composite to the substrate. The benefits of this type of application are that (1) FRP composites can be cut/adjusted to address odd shapes/orientations in the field; (2) FRP composites may be placed in multiple layers to achieve a certain design criteria; and (3) this type of application can allow for design flexibility in FRP composite compositions and orientations. Care must be taken to prevent air voids and premature cure in one fabric layer during wet layup application when multiple layers of fabric are added to a structural component. Furthermore, there should be no kinks or waviness in the fabric to avoid stress concentrations [35]. Throughout the report, the FRP composites described are wet layup systems unless otherwise specified as *laminates* or *plates* which are described in the next section.

Pre-cured (cured resin): Pre-cured and pre-shaped FRP composites (polymer and fibers) usually come in sheet form with multiple layers that can be applied to a structure with adhesive. The benefits of this type of application are that no field saturation is required and precured FRP composites typically have lower overall installation costs. For precured FRP composites, it is important that the adhesive layer is not too thick to prevent a weak bond to the substrate [35]. Pre-cured FRP composites can include directional fibers embedded in polymer, multidirectional fiber grids rolled into a coil, laminate strips to embed into pre-cut grooves in the concrete element to be strengthened, and pre-cured shells to be opened and fitted around columns. Pre-cured FRP composites can be combined with wet layup systems to achieve biaxial strengthening. Pre-cured FRP composites are often called *laminates* or *plates*.

Pre-preg (uncured resin): This type of fabric is impregnated with resin in the manufacturing facilities and remains uncured until application at a specific site. Pre-preg FRP composites are cured once applied to a substrate, usually by heating, and much care needs to be taken with storage and handling of prepreg FRP composites before use. An additional resin, or adhesive, may or may not be needed for attachment of the pre-preg FRP composite to a substrate. Fiber tows that are wound or mechanically applied to a substrate can also come in pre-preg form.

2.2.3. FRP Anchors

FRP anchors are used to carry tensile loads of externally bonded FRP composites into the structure to mechanically restrain the FRP composite or prevent premature FRP composite debonding failures [46]. FRP anchors more fully develop the tensile strength of the FRP composite [46, 47]. Several types of anchors have been utilized and include FRP U-jackets and FRP patch anchors to expand the FRP bonding area, concrete embedded FRP composites to improve bond strength and ductility, and spike anchors which insert into a pre-drilled hole of the substrate which is pre-filled with resin [48]. For spike anchors, fibers are inserted into the resin-filled substrates holes either as loose fiber bundles or as pre-cured dowel ends and the fibers opposite to the bundle/dowel ends are fanned or splayed outside of the holes onto the existing FRP system [47, 49, 50]. If the FRP anchor is run all the way through the substrate, fibers can be splayed on both sides of the hole. FRP anchors can be fanned in different configurations (*e.g.*, single fan, bow-tie, *etc.*) and at various dowel and fan angles [51]. Other anchorage methods include nailed metal plates, near-surface mounted rods, concrete embedment, mechanical substrate strengthening, and mechanical fastening which is described in the next section [48]. Further research is needed to establish reliable anchorage design criteria for structures [46, 48].

2.2.4. Mechanically Fasteners

Mechanical fastening of FRP composites by other materials or mechanical fastening of nonstructural materials to FRP covered substrates is also common in the field but not well-researched in terms of how these physical fasteners affect the strength and durability of FRP composites [52]. Specifically, increased stress concentrations in the FRP composite are possible and fibers adjacent to mechanical fasteners may become damaged. More guidance and research is needed on mechanical fasteners (*e.g.*, size and spacing) since they are commonly used to attach non-structural materials (*i.e.*, signs, shelves, *etc.*) to structures that may be covered with FRP composites. Mechanical fastening of FRP composites can be accomplished using shot pins, fasteners, nails, bolts, *etc.*, usually through the FRP composite [53].

2.2.5. FRCM (Fiber-Reinforced Cementitious Matrix) Composites

Fiber-reinforced cementitious matrix (FRCM) composites differ from FRP composites in that the matrix is cementitious rather than polymeric. FRCM composites consist of fabric grids and cementitious agents (*i.e.*, mortar) that serve as the matrix. FRCM composite design guidelines are provided in ACI 549.4 R-13 [54]. Compared to epoxy resins used in FRP composites, FRCM composites have better thermal resistance, fire resistance, are more compatible with concrete substrates, and are not sensitive to moist surfaces during application as is the case with FRP composites [55, 56]. Similar to FRP composites, FRCM composites are fast to install. FRCM composites are aesthetically similar to their underlying concrete substrates and do not require protective coatings/paint as do FRP composites. The fibers, usually in the form of sheets or fabrics, carry tensile stresses and can help a structure achieve increased axial, flexural, or shear strength. Similar to FRP composites, the volume content of fibers controls the modulus of elasticity for FRCM composites. Bonding of the fibers to the cementitious matrix is critical for load transfer and the adhesion between fibers and cementitious matrices is not strong [55]. Sometimes, resins are coated onto the surface of fibers to improve fiber/matrix adhesion.

A noteworthy downside of cementitious matrices is their low strain to failure, which is less than the strain to failure of polymer matrices and fibers (Figure 2.3). The tensile behavior (*i.e.*, stress-strain curve) is very different from an FRP composite alone, which has linear-elastic behavior until rupture of the fibers. As shown in Figure 2.3, the tensile behavior of FRCM composites consists of three phases with a bi-linear stress-strain behavior [55]. In phase one, the cementitious matrix primarily carries the load until cracking. In phase two, a multi-cracking process in the cementitious matrix begins in which the stresses from cracking transfer to the fiber fabric. Some debonding at the fiber/cementitious matrix occurs at this stage. In phase three, the FRCM composite behaves linearly until failure with the fiber fabric debonding followed by progressive rupture of the fibers [55]. Unlike FRP composites, for which failure occurs from fiber rupture at a high stress while the polymer matrix behaves in a ductile manner, the cementitious matrix of FRCM composites cracks easily under tension or shear, leading to failure by debonding of the fibers from the cracked matrix [55]. This is likely why FRCM composites are currently less prevalent in the US.

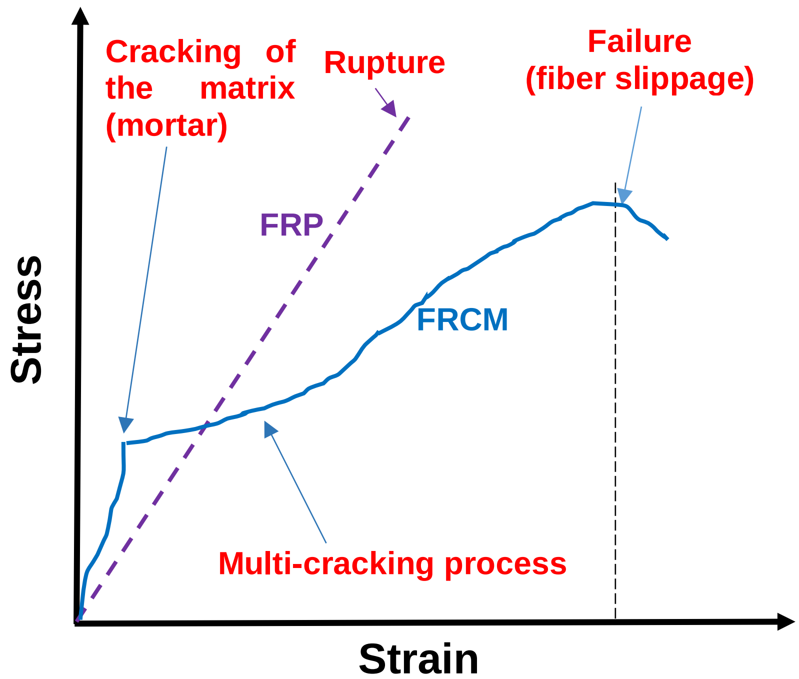


Figure 2.3 A comparison of the stress-strain curves for FRCM composites versus FRP composites [55].

In comparison to FRP composites, FRCM composites have better performance in the presence of UV radiation, high temperatures, fire, and moisture. The cementitious matrix of FRCM composites is also noncombustible and generally less toxic than resins used for FRP composites. FRCM composites are also permeable to moisture which allows moisture to travel through the FRCM composite unlike the FRP composite, thereby circumventing debonding issues from moisture build-up at the FR composite/concrete interface [57]. Furthermore, FRCM composites perform better than FRP composites in wet environments such as in European heritage masonry buildings where poor thermal insulation leads to condensation [58]. FRCMs also have the advantage of being easy to apply to irregular substrates and being able to maintain site aesthetics by matching the mortar matrix material to the substrate material [57, 59]. FRCM composites using inorganic matrices may be a logical choice in harsher environments, but more work is needed to improve bonding between fibers and matrices [58, 60].

2.2.6. Application and Benefits of FR Composites to Repair and Retrofit Structures

The most common use of FRP composites is on reinforced concrete (RC) structures, and FRP composites have historically been used as a supplement to internal steel reinforcement for tensile and shear strengthening [61, 62]. Common uses of FRP composites include repair to damaged RC structural components after collision, internal steel reinforcement corrosion, overloading, and extreme loads from hazard events (*e.g.,* seismic loads, blast loads, *etc.*). FRP composites are also used for strengthening of the gravity load-carrying system and seismic retrofitting of buildings and infrastructure. FRP composites have become a common method of seismic retrofit because of their use for improving confinement, which leads to increased ductility due to the development of higher compressive strains, of RC columns, pillars, and boundary elements, as well as shear strengthening of walls and boundary elements, and improving the shear transfer between different building components [63]. FEMA 547 describes the most common uses of FRP composites by practitioners in the seismic rehabilitation of various model building types [62]. As discussed earlier, in this report the “retrofit” terminology includes both strengthening for gravity loads and seismic retrofit of structural components. The different types of FRP composite retrofit strategies are described in more detail below and include strengthening of gravity load carrying systems, shear strengthening, and seismic retrofit.

Strengthening the gravity load-carrying system of a structure may become important if the use of a structure changes and more gravity load is expected than the original design of the structure. Gravity loads are vertical loads, so strengthening a gravity load-carrying system would involve strengthening the components that support vertical loads, such as columns, walls, beams and diaphragms. FRP composites can be used to strengthen the gravity load-carrying system by increasing the axial compression strength of a member through confinement. Beams and diaphragms can be strengthened by bonding the FRP composites to the tension face of these elements, which will increase the flexural strength of the members. Increasing the flexural strength of elements like beams and diaphragms leads to an improvement in the gravity-load carrying system.

Shear strengthening of a structure may be required when components are under-designed for the expected shear loads or new loads are placed on components that increase the shear demands of the structural elements. Under-designed structural elements, particularly concrete elements, may be identified by the lack of or sparse shear reinforcement in columns and beams. New loads that may increase the shear demands on a structure may include increased lateral loads, such as seismic or wind loads, or increased gravity loads. FRP composites can provide shear strengthening for different structural elements by acting as a substitute for missing internal shear reinforcement or supplement to existing shear reinforcement. This is accomplished for columns and beams by wrapping or partially wrapping (e.g. U-wrap) the element in the area of needed shear reinforcement. Walls can be strengthened for shear with FRP composites by placing horizontal FRP laminates along the face of the wall. Shear transfer between different building components can also be accomplished by tying these components together with FRP composites.

Seismic retrofits enhance the ability of a structure to withstand seismic loads. Seismic loads are usually lateral loads, so a seismic retrofit may focus on enhancing the lateral load-carrying system of a structure. Structures also perform better under seismic loads when they are more ductile versus brittle. The seismic retrofits can be designed to mitigate brittle failure mechanisms in structural components. FRP composites are popular to use in seismic retrofits because of the ability to increase ductility in a system and to strengthen the lateral load carrying components, such as columns and walls. FRP composites increase ductility and strengthen members through wrapping the elements and providing confinement. Using FRP composites as a retrofit technique may also increase the global energy dissipation capacity of the system, which improves the overall behavior of reinforced concrete structures.

FRP composites can also be used to retrofit structures made of materials other than RC, such as steel, timber and historic masonry, although there has been relatively less research on FRP composite application to these structures. Using FRP composites to rehabilitate steel structures has advantages over the use of additional steel due to the high strength-to-weight ratio, the resistance of FRP composites to corrosion, and the ability to conform FRP composites to curved and irregular shapes of steel components [64, 65]. There have been several applications of FRP laminates applied to steel structures to repair and strengthen degraded girders and beams, and studies have shown that CFRP composites can restore and add capacity to these beams and extend the fatigue life [66]. Research such as improvement of steel surface treatment, selection of adhesives, and understanding of bond-slip behavior is needed to increase the acceptance of this retrofit technique [64, 65].

The use of FRP composites as a strengthening material for timber structures has been investigated for more than 25 years. The effectiveness of adding CFRP laminates to the tension face of timber beams has been investigated with significant improvement in some mechanical properties observed, such as the flexural capacity [67]. There is still, however, very little documentation about the use of FRP composites to strengthen timber structures and more research is needed to investigate the long-term performance of an FRP-timber system, in terms of durability, fatigue and creep [67, 68].

FRCM composites have also been in development and use in different capacities since the 1990s. FRCM composites can be identified with several different names, such as textile reinforced concrete (TCM), textile-reinforced mortar (TRM) [69, 70], mineral-based composites (MBC) [71], and fiber-reinforced cement [72]. FRCM composites have been used in many applications in Europe [73], and design guidelines (ACI 549.4R13) are available for their use in the United States [54]. FRCM composites are mainly used on concrete and masonry structures, and the advantages of using FRCM composites for repair or retrofit is its compatibility with concrete substrates, ease of installation, porous matrix structure, good performance at elevated temperatures, and long-term durability [54]. Some hindrances to more widespread use of FRCM composites may be related to limited design standards, lack of standardized methods for testing the mechanical behavior, and fiber/cement compatibility issues.

2.2.7. Intended Lifetime of Repair and Retrofit

Typical service life for buildings and infrastructure range between 50 years to 100 years, depending on the purpose of the structure and the type of materials used in its construction [74]. During their service life, structures are constantly aging under chemical, physical and mechanical stresses, and these stresses can deteriorate functionality. For example, an estimated 9 % of all bridges on the National Bridge Inventory were found to be structurally deficient and required repair or replacement in 2016 according to the ASCE Report Card [75]. In recent years, the demand to retrofit aged structures has increased for buildings and infrastructure and FR composites have become a competitive alternative to steel reinforcements to meet these demands. Specifically, FR composites provide high strength, a low profile on structures, and corrosion resistance when compared to traditional steel reinforcements.

A recent scan of FR composite used in transportation infrastructure reveals that some FR composite retrofit techniques, such as applying externally bonded FRP to damaged bridge girders, have been in use for the past 25 years [13]. In terms of FR composite use to retrofit buildings, FRP plates were first used to strengthen RC beams in buildings in the mid-1980's in Europe, and expanded for use in the United States by the late 1990's [1]. Even with this history of FR composite use in buildings and infrastructure, there are still aspects of incorporating FR composites into retrofit design that are still maturing and in need of further research. Regarding the mechanical properties of the FR composites and strengthening capability to the structure, the lack of durability data or access to data is a concern [3, 76]. For example, the reports that describe the long-term performance of FRP composites in the field provide valuable information but are limited by material type, duration (5+ years in this example), and single outdoor exposure sites [77]. Although existing codes and guidelines (*e.g.*, ACI 440.2R-02) for use of FRP composites as external structural reinforcements provide environmental reduction factors, interrelations among environmental degradation processes of constituent materials (fibers and resins), the FR composite itself, and FR composite/concrete members at multi-scales and loading modes have not been comprehensively studied. Other factors can also influence the durability of the FR composite system and require further investigation. These factors include manufacture methods, application method to a substrate, quality control, and installation of the FR composites.

The resistance of FR composites to fire and to degradation under different environmental conditions, such as freeze-thaw, salt water, and UV radiation have been studied, but long-term durability data in the field are sparse [78-80]. The use of accelerated conditioning tests (synonymous with accelerated weathering protocols) is necessary to identify FR composite degradation modes on a reasonable time-scale, but estimation and validation of FR composite service life requires more field data. Some early projects and demonstrations have shown that FRP composites can have excellent durability characteristics in warm and cold climates for several years [77, 81]. Data are still needed that assesses the ability of FR composites to last up to the remaining life of a structure, which could be 30 years or more.

In repair applications, some users have developed guidance for the expected service life of the FR composite repair. The New York State DOT (2002) issued guidance stating that FRP composite repair is expected to last the rest of the expected service life of the infrastructure [82]. Specifically, NY DOT states that long-term repair on sound concrete should be designed to last at least 20 years. If the cause of the concrete deterioration is not fixed prior to repair, or if the concrete is not sound (*i.e.*, free of excessive cracks, flaws, fissures, voids with strength and cohesiveness according to the International Concrete Repair Institute (ICRI) [83]) or variation from an accepted standard, then the repair should be considered temporary, and could last between 5 years and 7 years [82]. Although not explicitly described in the guidance documents reviewed for this report, other stakeholders and DOTs may have similar guidance when designing for rehabilitation or retrofit with FR composites.

2.2.8. Degradation and Failure Mechanisms of FR Composite Materials and Interfaces

FRP composite degradation mechanisms are divided into several categories that include some of the specific constituent materials and all of their interfaces: within the polymer matrix, within the fiber, at the fiber/polymer interface, at the FRP composite/adhesive interface, or at the adhesive/concrete substrate. For the polymer matrix, which tends to be epoxy, moisture absorption from high humidity or immersion in water can cause plasticization, or polymer swelling, which can decrease the glass transition temperature (T_g). A decreased Tg increases the network mobility of the polymer chains and decreases the modulus of elasticity of the polymer, thereby leading to poorer performance of the FRP composite [84, 85]. Furthermore, exposure of FRP composites to temperatures near or above the T_g can also affect mechanical properties. The polymer matrix can also be degraded by free radicals formed during UV exposure. These radicals may affect the FRP composite tensile strength and modulus of elasticity after extended UV exposure times [86]. UV degradation of the polymer matrix can also lead to exposure of the fibers and polymer cracking which can increase moisture penetration and lead to further moisture-induced degradation [86].

For fibers, the UV-resistance of glass and carbon reinforcing fibers are typically better than polymer fibers (aramid fiber like Kevlar) [33, 34].

For the FRP composite (fibers + polymer matrix), environmental degradation processes can lead to debonding between the fiber and matrix, matrix cracking, and interlaminar debonding, or debonding between the FRP composite layers [87]. For all fibers, moisture uptake can disrupt the interfacial regions between the polymer matrix and the fiber sizings (*i.e.*, coatings for fiber/matrix compatibility) or surface treatments [33, 88]. For glass fibers in particular, moisture can even hydrolyze silane-based sizings, which can detrimentally affect fiber/matrix adhesion [33, 34]. Glass fibers are also subject to stress corrosion in which moisture, alkaline conditions, acidic conditions, and other chemical exposure can lead to glass hydrolysis while under static fatigue conditions [33, 34]. Carbon fibers are not as susceptible to moisture-induced degradation. Plasticization of the polymer matrix can also create stresses at the fiber/polymer matrix or between FRP composite layers, thus decreasing fiber/matrix adhesion and interlaminar adhesion [33]. This process is highly dependent on the type of polymer matrix. The rate of moisture absorption in FRP composites depends on temperature and pH. Fickian models, two-stage models, and the Langmuir model have been proposed for the rate of moisture absorption as a function of temperature and material thickness [18]. Absorbed moisture in FRP composites can create mechanical stress during freeze-thaw cycling and the expansion of frozen water can lead to the formation of cracks and delaminations in FRP composites. In moist environments, alkaline conditions can also accelerate hydrolysis at glass/polymer matrix interfaces in FRP composites, leading to a decay in the strength of the composite. This is particularly important because FRP composites are often applied to concrete, which exposes the FRP composite to alkaline conditions from the concrete. Exposure to UV irradiation causes photochemical damage of FRP composites near the exposed surface, and UV-induced surface degradation can eventually lead to the formation of cracks, which can allow moisture and oxygen to penetrate into the resin to cause more degradation [86]. Removal of UV-degraded resin, or resin photoproducts, by rain or moisture may also occur and expose fresh resin matrix to continued UV-induced degradation. Interactions among various surface damage mechanisms can occur in the outdoor environment and understanding the effects of multiple simultaneous damage mechanisms on FRP composite tensile strength loss and modulus of elasticity loss is important to ensure that the retrofitted structure maintains its designed performance level.

The interfaces between the FRP composites and the adhesive and between the adhesive and concrete surface are additional locations of degradation [87, 89]. Debonding is a concern when FRP composites are attached to concrete and can occur between these layers. There is still uncertainty in experimental data and models for predicting the effective lifetime of FRP composite bonds, so more research is needed to understand the bond and mechanical behaviors that can cause premature failures of FRP composite assemblies [79]. During installation of FRP overlays, the impermeability of FRP composites to water must be considered as moisture transmission in and out of materials such as masonry and concrete exterior walls is common and necessary. FRP composites can affect this process in some applications leading to potential debonding problems during use since moisture builds up behind the FRP overlay [79]. Thermal fatigue by freeze-thaw cycling also occurs because water expands upon freezing at the FRP-concrete interfaces and leads to stresses that result in debonding failures. Application of dynamic loading to an FRP retrofitted structure can lead to interfacial degradation by mechanical fatigue. Under sustained loading, creep behaviors of the FRP composite adhesive can create interfacial stresses at the-concrete interface and lead to debonding; this can depend on the magnitude of the glass transition temperature and application temperature [90, 91].

In addition to environmental degradation on bonding properties, environmental conditions on-site must also be considered. Some saturating resins can cure more quickly than the time it takes to install the saturated fiber fabrics at temperatures above 32 °C (90° F) and some saturating resins may not fully cure or cure too slowly below 4 °C (40° F) [10]. Furthermore, moisture content in the concrete can also affect the bond between the FRP composite and the concrete during saturating resin cure [10, 92]. For this reason, the plastic sheet method should be used to assess whether moisture forms on a polyethylene sheet taped to the concrete during the time period it would take the saturating resin to cure [93]. If water forms on the polyethylene sheet, then the concrete requires further drying before FRP composite application [10, 92]. This also means that application of FRP composites in rain should be avoided. During FRP composite application, FRP witness panels, or free-standing FRP composites, are usually prepared for laboratory tensile testing and to determine the extent of epoxy cure under site conditions. Concrete surfaces must also be prepared properly prior to FRP composite use to avoid debonding issues over the long-term. Substrate repairs may include removal and replacement of unsound concrete, rounding of corners, crack repair, or corrosion repair of exposed rebar [7, 45]. Concrete surface preparation can include cleaning of the surface, application of putty to voids and rough edges, concrete drying if necessary, and achieving a specified surface profile by acid-etch, grinding, or shotblasting [7, 10, 45].

For FRCM composites, durability and failure concerns also exist, which are highlighted by the acceptance criteria provided in Acceptance Criteria (AC) 434 (International Code Council-Evaluation Service) for masonry and concrete strengthening using FRCM composites. Specifically, AC434 recommends examining shrinkage of the cement matrix, examining if voids are formed in the FRCM composite, and exposing FRCM composites with straight and pre-bent fibers to aging in heated water, saltwater, and alkaline solution, freeze/thaw cycling, fuel resistance tests, and flammability resistance tests. In terms of durability, Aboleda et al. found that the residual tensile strengths and pull-off bond strengths of FRCM composites tested according to AC434 acceptance criteria showed no significant loss of FRCM composite strength under freeze/thaw cycling, saltwater immersion, and alkaline solution immersion [94].

2.3. Materials Characterization Methods to Assess FRP Composite System Performance at Three Different Scales (FRP Composites, FRP Assemblies, and FRP Retrofitted Structures)

This section describes test methods and measurements used to characterize FRP composite system performance initially and over the structure's lifetime at three different scales. The smallest scale of characterization described in this report is on the FR composite material alone (2.3.1). At a slightly larger and more complex scale, FR composites are attached to substrate specimens for characterization. This configuration is defined as an FR composite assembly throughout the report (2.3.2). At the largest scale of characterization, FR composites are attached to structural components or structures (2.3.3). FRCM composite performance is not described in this section since these materials are not as commonly used as FRP composites, but FRCM composite performance requirements are briefly described in Section 2.2.8.

2.3.1. Characterizing FRP Composite Performance

2.3.1.1. Tests Methods for the Initial Properties of FRP Composites

Tests that determine the initial properties of FRP composites are most common for the composite itself and not for the FRP assembly (*i.e.*, the FRP composite attached to a substrate). Several types of measurements are established for assessing the initial FRP composite properties. In this sub-section, tests that measure the performance of the FRP composite itself are described. Many of these tests have the potential to be modified for FRP composite assembly testing and consensus on new or modified tests are still needed in many areas.

The most commonly tested properties of FRP composites prior to their use are mechanical properties with the goal of determining force and deformation limit states and failure modes [7]. Mechanical tests typically include tensile tests of FRP composites to obtain a stress/strain curve that gives important mechanical properties such as the stiffness per unit width, the force carrying capacity per unit width, and the ultimate tensile strain [95]. At the FRP composite rupture stress, the FRP composites are no longer viable in a structural component, so it is important to understand the stress at which this occurs and not exceed this level of stress in the field. Tensile tests can be performed in either the transverse (perpendicular to the fiber direction, ASTM D7617/D7617M) or longitudinal directions (parallel to the fiber, the strong direction) depending on the application (ASTM 7565/D7565M, ASTM D3039/D3039M) [95, 96]. Standardization of tensile tests for FRP composites in civil engineering applications can be found in ASTM 7565/D7565M [95].

Another important type of mechanical test for standalone FRP composites involves flexural testing or three-point bending tests. In this case, the FRP composite is placed on two fulcrums, and a concentrated load is applied from the center at a controlled rate to create bending stresses. The deflection of the FRP material and the applied load are typically measured to calculate the flexural strength and flexural modulus (ASTM D7264/D7264M) [97]. This test can also be applied to FRP assemblies as described later.

Interlaminar shear testing involves gripping the FRP composite at the top corner of one side of the composite and the bottom corner of the other side of the composite and applying loads at the top and bottom corners in opposite directions. The applied load pulls the fiber layers in the FRP composite in different directions to induce interlaminar shear stress [8, 86]. Interlaminar shear strength can be measured by the short-beam method (ASTM D2344/D2344-M) or the V-Notched Beam Method (ASTM D5379/D5379-M) and the adhesives of FRP laminates are tested with tension loading by ASTM D3165 [98-100].

While under a constant applied load, FRP materials have the potential to creep. Creep is a time-dependent deformation of the FRP composite below its rupture strain when placed under an applied load. Creep behavior can be enhanced at elevated temperatures and high loads. Testing usually takes place under a constant load and is done in compressive, flexural creep, and tensile creep-rupture modes using ASTM D2990 [101].

The chemical properties of FRP composites can be measured prior to use and after use but this is often not done in practice since the durability of FRP composites is not broadly tracked in the field. Chemical properties can be measured with attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR), which primarily provides chemical information about the polymer matrix [102]. Raman spectroscopy may also be used to assess chemical information about the polymer matrix and fiber composition. For carbon fibers specifically, the signature D (defective carbon) and G bands (graphitic carbon) for graphitic carbon can be used to identify the fibers in the matrix and evaluate their composition [103, 104]. The thermal properties of the FRP composite can be assessed to determine the glass transition temperature and creep/fatigue behavior [7]. Imaging, typically by scanning electron microscopy (SEM), is used for cross-sectional analysis of FRP composites to assess microcracking and voids in the FRP composite [86, 102]. Other imaging techniques may also be useful depending on the size of the fibers. Acoustic emission methods and laser-based techniques are used to assess voids and cracks in FRP composites [105]. Some of these techniques, such as Raman, ATR-FTIR, acoustic emission, and laser-based techniques, would be useful to track FRP composite changes in the field without invasive mechanical testing. However, cost issues and a lack of developed approaches to non-invasively track durability in the field have so far limited the use of these techniques in practice.

Other important FRP composite properties include composite thickness, fiber surface chemistry, and fiber orientation. These properties are typically provided by the manufacturer and are crucial to evaluate prior to use on structural components. Voids within the FRP matrix are measured using ASTM D3171 as excess voids can lead to fiber slippage and strength reduction [8, 106]. The glass transition temperature, degree of cross-link/cure, and presence of additives in the thermoset polymer are also important information needed in the material and structural design process [7]. The glass transition temperature, the temperature at which polymer chain mobility starts to occur, can be determined with ASTM E1640 (Dynamic Mechanical Analysis), ASTM E831 (Thermomechanical Analysis), and ASTM E1356 (Differential Scanning Calorimetry) [7, 8, 107-109]. The coefficient of thermal expansion (CTE), a material property that indicates the extent to which the FRP composite expands during heating, is important to understand how the material will generate internal stresses when applied to a substrate. ASTM D696 (Vitreous Silica Dilatometer) or ASTM E831 (Thermomechanical Analysis) are typically used for CTE measurements, and a close match of the FRP composite CTE and the substrate CTE must be made to avoid internal stress build-up [108, 110]. Further understanding of the relationship between polymer matrix properties and FRP composite performance in practice may be useful, especially when qualifying new polymer formulations for use in infrastructure applications.

2.3.1.2. Long-term Property Testing for FRP Composites in the Laboratory and the Field

FRP composites may be exposed to a variety of environments in the field. FRP composites might be exposed to moisture, dry conditions, salt water, alkalinity and acidity, freeze/thaw cycles, high temperatures, and UV radiation all while experiencing sustained, frequent, or infrequent stress [6, 8, 17, 61, 86, 102]. Many studies have tested different variations of environmental processes for FRP composites alone and acceptance criteria exist in ICC-ES AC125 for externally applied FRP composites [8]. These tests typically involve immersing FRP composites in media under controlled conditions or placing FRP composites in environmental chambers [6, 61]. Specifically, AC125 recommends that the following environmental conditions are tested: UV exposure with or without added paint for > 2000 h with cycles of water spray, cycles of freeze/thaw, alkali soil resistance, and aging in hot water, hot saltwater, hot alkaline water, and under dry heat for 1000 h, 3000 h, or 10,000 h. FRP composites are typically tested for changes in tensile properties after environmental exposure, with 90 % retention of tensile properties required for 1000 h of exposure and 85 % retention of tensile properties required after 3000 h of exposure. Signs of cracking, crazing, checking, and chalks are visually examined with a microscope at 5x magnification. Glass transition temperature and interlaminar shear length are also commonly tested after environmental exposure [8]. Many durability studies have been conducted on standalone FRP composites, but not as many studies have examined FRP composites under stress while being exposed to environmental conditions.

Other approaches to test property changes of FRP composites in the laboratory or in the field depend on whether the measurement targets the polymer matrix, the fibers, or the interface of the two. Currently, a combination of measurement approaches is preferred since there are several types of FRP composite degradation modes that can potentially lead to failure. Formation of cracks, fiber debonding from the polymer matrix, polymer creep/relaxation, and polymer matrix degradation and removal are a few possible property changes that must be considered before and after environmental exposures [86, 102, 111]. Many of the material property changes measured after accelerated conditioning in a laboratory can also be measured for FRP composites exposed outdoors. For example, measurements of glass transition temperature, changes to tensile strength and interlaminar shear strength, and visual observation of cracking can be made for outdoor-exposed FRP composites whether they are standalone or applied to a substrate. However, very few studies have comprehensively investigated outdoor degradation of FRP composites due to the long time (*i.e.*, years) it takes to degrade polymeric samples outdoors. Thus, further experimental research is needed on outdoor degradation of FRP composites. This is in addition to degradation of the bond between the FRP composite and the substrate, usually concrete, which is the focus of a later sub-section.

FRP composite property changes have been measured in a variety of ways. Most typically, the mechanical properties of the FRP composite before and after an environmental process are compared using tensile, flexural, creep deformation, or interlaminar shear testing. Digital image correlation (DIC) acquisition has been used during mechanical testing to compare the full-field displacement fields of FRP composites before and after environmental exposure [112, 113].

Fiber debonding from environmentally exposed samples can be assessed with imaging [61, 102]. SEM can be used to image the cross-section and determine if fibers appear at the surface of the composite after polymer degradation. Raman spectroscopy can be used to identify fibers at or near the composite surface after polymer matrix degradation and to identify new peaks from polymer matrix and fiber degradation [27, 103, 104]. And chemical changes to the polymer matrix can be measured with ATR-FTIR spectroscopy [86]. Polymer removal from the composite during degradation is measurable with mass loss or cross-sectional imaging for thickness loss [102]. Raman and ATR-IR spectroscopy are typically conducted in a laboratory setting but further advances in handheld instruments may make them useful for *in-situ* testing of FRP composites in the field.

Debonded areas and cracks within the FRP composite that form during environmental exposure can be assessed with imaging at the cross-section [86]. Acoustic emission tests, thermography, laser reflection, and laser-based acoustic tests can also be used to measure the internal change in the FRP composite material before and after environmental exposure [30, 105]. In this case, cracks and debonded areas lead to a change in the signal that returns to the instrument. These techniques are typically non-destructive (ND) and most practical for *in-situ* use but require further development and eventually standardization. These tests are also useful for FRP assemblies as described in the next sub-section. Moisture entrapment using a moisture absorption setup or sophisticated neutron imaging techniques can also provide information on changes to interfacial bonding interactions between the fibers and the matrix as a function of relative humidity [17].

2.3.2. Characterizing FRP Assembly Performance

This Section describes methods to characterize the performance of the FRP assembly, or the FRP composite attached to the substrate, which is typically concrete [18]. Two types of test methods are discussed: 1) laboratory measurements to pre-qualify the system and 2) *in-situ* tests to ensure quality control both at installation and to monitor performance over the service life of the structure. These tests methods could be further divided into two categories: non-destructive (commonly *in-situ*) and destructive (mainly done in a laboratory or on cored specimens).

The parameters to be monitored or tested could be defined as: 1) material properties, especially of the FRP composite (see section 2.2.1), 2) the adhesion of the FRP composite on the substrate and 3) the condition of the concrete substrate.

2.3.2.1. Initial Performance of FRP-Concrete Assembly

Inspection

During installation, quality-assurance and quality-control programs and criteria should be followed by anyone associated with the install, including the manufacturers and contractors [7]. Documentation should be made of temperature, relative humidity, other weather conditions, surface temperature of concrete, concrete moisture content, surface preparation methods for the concrete, cleanliness of the concrete surface, use of an auxiliary heat source during curing, width of cracks not repaired prior to FRP composite application, FR fabric or laminate batch numbers and locations in the structure, mixing ratios, general appearance of primers, putties, saturating resins, other adhesives, and coatings, and length/progress of cure time [7, 10]. However, more research is needed to show how the initial conditions of the concrete during FRP composite application affects long-term performance of the FRP composite bond to the concrete. Furthermore, pull-off test results should be recorded (described later), locations of delamination or air voids between the FRP composite and the concrete, as well as conformance with installation procedures. FRP witness panels, or free-standing FRP composites prepared at the same time as the FRP composite applied to the substrate on the job-site should also be collected and sent to a lab to replicate the on-site cure conditions of the materials. Part of the witness panel or a mixed cup of resin from the job site can be used to determine the degree of cure with ASTM D3418 [7, 10, 114]. For qualitative assessment of the degree of cure on the job site, tackiness and hardness of work surfaces or retained resin samples can be monitored [7].

For evaluation and acceptance, FRP composites must conform to design drawings, especially in terms of fiber orientation and placement of the FRP materials. Material properties need to be determined with witness panels sent to a laboratory for evaluation of tensile strength and modulus of elasticity, lap splice strength, hardness, and glass transition temperature (see testing procedures in previous section) [7]. Records of the witness panels should be kept for a minimum of 10 years by the licensed design professional [7].

Non-destructive Field Testing

Initially, to detect defects in the bond between the FRP composite and the substrate, ACI 440.2R-17 states that inspection methods such as acoustic sounding (*e.g.*, coin tap method), ultrasonic sounding, and thermography should be capable of detecting delamination on a surface of 1300 mm^2 or larger [7]. Delaminations of this size or smaller are acceptable as long as they represent no more than 5 % of the surface area. Further guidance for larger voids is provided in ACI 440.2R-17 [7].

After installation and visual inspection, the most common non-destructive field test is the coin-tap test, which is an acoustic sounding technique using a coin to listen to sound radiated by the structure after tapping on the FRP assembly [7]. Mute/hollow sounds occur in the defective regions where voids are present [7]. Acoustic sounding is also performed with a small hammer sounding method [7]. In the field, non-destructive techniques also include an acoustic laser technique that is performed by initiating vibrations at the FRP assembly with acoustic waves and characterizing the resulting vibrational behavior with a laser beam in order to detect defects located near the surface [76, 105]. Ultrasonic (*i.e.*, higher frequency acoustic waves) inspection techniques use an ultra-wide band and measure reflected waves with good spatial resolution to detect defects and obtain characteristic responses of different materials [115]. Ground-penetrating radar has also been used to detect surface voids but may not be able to effectively detect FRP composite debonding due to surface wetness and cleanliness [116]. Infrared thermography analyzes the intensity of infrared radiation dissipated by materials after heating at their surfaces. Defect characterization has been conducted using IR thermography and is currently more of a qualitative measurement [117].

Destructive Field Testing

The adhesion status of the FRP composite to a substrate is quantitatively evaluated using pull-off testing, a destructive test method. ACI 440.2R indicates that tension adhesion tests (*e.g.*, pull-off tests in ASTM D7522 or ICRI 210.3R) should be conducted by drilling through FRP assemblies to about 6 mm into the concrete substrate, applying a steel or aluminum disk with epoxy and pulling off the core at a controlled rate with an adhesion tester [118, 119]. Currently, ACI 440.2R states that pull-off tests should be used to assess the tensile strength of the concrete alone (ASTM C1583/C1583M) and compressive strength of concrete cores (in accordance with ACI 562) prior to FRP composite application [7, 120, 121]. For pull-off tests of FRP composite assemblies, guidance documents indicate that failure of the FRP assembly should occur in the concrete and pull-off strengths of the concrete should exceed 1.4 MPa (200 psi) [7]. Failure can occur in two ways: 1) a cohesive failure occurs when there is a break within a layer and 2) adhesive failure occurs when there is a break between two layers. Cohesive failure can occur within the FRP composite layer, within the adhesive layer, or within the concrete layer and adhesive failure can occur at the FRP/adhesive interface or at the adhesive/concrete interface. A mixture of these failure modes can also occur [118, 119]. Adhesive failure occurs when the FRP composite debonds from the adhesive or the adhesive debonds from the concrete during the pull-off test and indicates that there was poor adhesion of the FRP composite to the concrete. In practice, high variations in pull-off strengths and multiple failure modes are often reported *(e.g.,* higher than 30 % variation among the pull-off strengths as reported by Mata et al.) [122]. Potential sources of variability that influence pull-off test results include heterogeneity of the substrate, coring conditions (*i.e.*, depth, perpendicularity, and torsional stress), variations of adhesives (resin-hardener mixing ratio, voids), disk surface cleaning, and concrete surface preparation [123, 124]. Generally, a few pull-off tests (*e.g.*, 2-3 tests) are conducted in a location of the structure that minimally affects performance, which makes the results rather localized. Further guidelines on this test appear to be needed.

In addition to the pull-off adhesion test, peel tests, and lab shear tests are also used to evaluate fracture toughness of bonds between FRP composites and concrete [87, 125]. For both peel tests and shear tests, FRP assemblies are prepared with the FRP composite extending beyond the concrete edge. Peel tests measure the strength it takes to peel the FRP composite off the concrete in an upwards direction while shear tests involve applying force parallel to the FRP composite until debonding occurs [126]. Although both tests are useful to assess debonding changes after accelerated conditioning, the tests are not widely used on structures because FRP laminates have to be prepared at concrete edges or in locations that are not usually of interest for debonding measurements and portable equipment for *in-situ* tests is not widely available [87].

Laboratory Tests

Laboratory tests are not typically conducted on FRP assemblies from the field. Usually tensile tests are conducted on standalone FRP composites in the form of witness panels (ASTM D3039/D3039M and ASTM D7565/7565M) and more detailed guidance may be useful for consistent results in testing laboratories [7, 95, 96]. Since FRP debonding from substrates is a common issue, addition of witness panel assemblies (*i.e.*, the FRP composite attached to the substrate) to laboratory testing requirements may be worthwhile. However, it is difficult to remove both the substrate and attached FRP composite on-site for this testing. Instead, analysis of the interface of the FRP composite and the substrate from pull-off test samples may be useful for further testing in the laboratory, especially for durability testing. Many laboratory tests are used for standalone FRP composites that could be applied to FRP assembly testing both before and after accelerated conditioning. For long-term studies, baseline measurements are needed of the initial FRP assembly, in both the FRP composite and at the FRP composite-substrate interface.

2.3.2.2. Long-term Performance of FRP Assemblies

Inspection

ACI 440 states that the owner of a retrofitted structure should periodically inspect and assess the performance of FRP composite systems. A visual inspection should involve looking for changes in color, debonding, peeling, blistering, cracking, crazing, deflections, and signs of internal steel corrosion. Non-destructive testing and destructive pull-off tests are recommended [7]. The specific time frame in which FRP composite inspection should take place is not generally provided in a guideline. Nor is there any guidance on inspecting FRP composites after a seismic event. However, the NY State Department of Transportation (NYSDOT) recommends that all FRP retrofits should be inspected within (3 to 4) months of installation by Regional or Structures Division staff involved with the design; other states may have similar guidelines [82]. Recommended NY DOT inspection intervals after that point are every two years for confinement repairs, which are contact-critical or do not depend on the interface between the FRP composite and the substrate. For inspection intervals for FRP composites used in strengthening applications, a (9 to 10) month inspection followed by inspections every two years is recommended since the application is bond-critical and depends on the FRP composite-substrate interfacial integrity [82].

Non-destructive Field Testing

FRP composite debonding is one of the most common failure modes of FRP composites, and moisture entrapment has been shown to be a critical factor in the debonding process [17]. To assess debonding, visual, coin tap, IR thermography, acoustic, and ultrasonic techniques are non-destructive techniques that can be used. Visual observations and the coin tap method are most commonly used in practice to assess the long-term performance of FRP assemblies. Guidance on the number of permissible delaminations are provided in ACI 440, and above these thresholds, repair of replacement of the FRP composite may be warranted [7]. More *in-situ* test methods using nondestructive inspection methods could help improve the ability to monitor FRP composite debonding.

Destructive Field Testing

In the field, only a few studies have involved destructive pull-off tests after long-term outdoor exposure of FRP composites attached to structures. The purpose of these destructive tests was to determine the integrity of the FRP composite bond. One study examined pull-off test results for FRP composites applied to the Florida Skyline Bridge in Tampa Bay, Florida before and after 6 months and 18 months of outdoor exposure [127]. After 18 months of outdoor exposure, a greater fraction of adhesive failure was observed with pull-off tests. The study also tested the effect of a paint coating on bond degradation outdoors but no apparent effect on FRP debonding was observed [127]. Separate FRP assemblies exposed outdoors in Tampa, Florida for 18 months were also tested for adhesion strengths using three-point bending tests and only minor losses of adhesion strength were observed, likely due to the difference in mechanisms between pull-off tests and three-point bending tests [127]. A report by the University of Florida also conducted pull-off tests on several different bridges and found that 35 % of the tests gave adhesive failure or a mixed failure mode [16]. However, initial pull-off test results were not always available for comparison and it was challenging to determine if the adhesive failure observed was from installation practices rather than durability issues. Moreover, higher variability is often reported in the adhesion strengths obtained by pull-off tests in the field [122]. In general, more pull-off test studies to assess long-term degradation of FRP composites are needed in different environments and with initial pull-off test data for the particular structure [16]. Furthermore, for pull-off tests that have adhesive failure or do not meet bond strength requirements, further guidance would be useful for the contractor to decide whether or not concrete repair, FRP composite replacement, or more pull-off testing is needed.

Laboratory Testing

For research studies, laboratory tests for standalone FRP composites are usually performed before and after accelerated conditioning as described in Section 2.3.2.3. Many of these same tests can be applied to FRP assemblies, either by testing the attached FRP composite itself, the FRP composite-concrete interface, or the entire assembly.

The performance of aged FRP assemblies has been assessed with mechanical, physical, and chemical tests. For FRP assembly laboratory specimens, ACI 440.9R recommends using concrete beams with 100 mm square cross section, a block length of 350 mm, and a clear span of 300 mm [6]. Only one layer of FRP fabric should be applied to this concrete beam. After accelerated conditioning or long-term outdoor exposure, the FRP assembly can be mechanically tested with pull-off tests or the three-point beam bond test (*i.e.*, three-point bending) where a notch is placed in the center of the beam to represent cracked concrete and allow for a predetermined debonding path from the notch outwards. Three-point-bending tests are tests that can be used for FRP assemblies before and after weathering according to ASTM D7958/D7958M [128]. With the pull-off test, companion standalone FRP composites should be fabricated at the same time and tested with the ASTM tensile tests described earlier [6]. Micro-Fourier Transform Infrared Spectroscopy, Raman spectroscopy mapping, and imaging techniques (optical or electron microscopy) may also be used to assess the moisture content, fiber and polymer matrix degradation, and interfacial chemical bond degradation of the FRP assembly before and after long-term or accelerate aging [19]. Research with techniques such as Raman spectroscopy and nanoindentation have only been used to assess the bond between neat epoxy (no fibers) and cement or concrete, and future work is needed to assess the bond between FRP composites and concrete and how the adhesive bond changes after environmental exposure [19, 129].

Most of the studies on long-term performance of the FRP assembly focus on the adhesion characteristics to the concrete substrate under various environmental conditions (UV, temperature, moisture). The environmental conditions are typically selected to accelerate the deterioration of the FRP assembly and do not always reflect specific field conditions (*e.g.*, water immersion bath). Bond strengths are typically measured using pull-off tests and three-point bending tests (also called three-point beam tests), with cohesive failure (*i.e.*, failure in the concrete) being desirable and adhesive failure (*i.e.*, failure at the FRP composite-concrete interface) being undesirable. Accelerated conditioning protocols for long-term lab tests require continuous water immersion of FRP assemblies at 50 °C ± 3 °C for 3000 h without sustained stress. As a control for accelerated conditioning, FRP assemblies should be exposed in air to standard laboratory conditions at 23 °C ± 3 °C and 50 % ± 10 % relative humidity [6]. Tatar et al. mentions concerns about accelerated conditioning at temperatures higher than the glass transition temperature of the epoxy and showed that the accelerated conditioning protocols may give an overly pessimistic representation of outdoor degradation [127]. Specifically, with dry heat, FRP assemblies were found to have decreased bond strength and fail adhesively near or above the glass transition temperature with shear tests [130]. This was not the case below the glass transition temperature [130].

In an accelerated conditioning study by Tatar et al., bond strengths obtained by three-point bending tests and by pull-off tests decreased after immersing FRP assemblies in water at 30 °C, 60 °C and exposing them to 100 % relative humidity at 60 °C [127]. Higher water temperature was correlated with more loss of bond strength for both three-point bending tests and pull-off tests than lower temperatures. A relatively clear transition from cohesive failure to adhesive failure using pull-off tests was found, which was not observed by three-point bending tests. However, trends in bond strength reduction were consistent for both tests [127]. Since the three-point bending tests and pull-off tests vary in the mechanism tested, interpretation of the bond test results and adaptation to structural design might require additional research. Karbhari et al. investigated bond degradation of GFRP and CFRP assemblies using pull-off tests after 24 months of water immersion at room temperature and high humidity exposure at 38 °C [87]. Tuakta et al. assessed bond degradation using peel tests and shear tests after 8 weeks of FRP assembly immersion in water at 23 °C and 50 °C and after exposure of separate assemblies to wet/dry cycles [125]. Similar bond degradation results were obtained by Tatar, Karbhari, and Tuakta for FRP assemblies immersed in water or exposed to high humidity with lower bond strengths or fracture toughness observed [87, 125, 127]. Tatar reported a similar bond reduction for the 100 % RH at 60 °C compared to the 60 °C water immersion [127]. Karbhari reported similar bond reductions between water immersion at 23 °C and 95 % RH at 38 °C [87]. Overall, more work is needed to compare mechanisms of adhesion loss and failure in practice to mechanisms and failures observed with available adhesion tests to provide better correlations for models. Furthermore, aging times and conditions vary significantly in many studies. Increased consistency in experimental results could improve understanding of FRP assembly degradation for design considerations. So far, bond durability factors have been proposed as a safe design value for conservative estimation of bond durability [131-133]. Furthermore, experimental approaches using shear bond strength have been described for assessing bond durability before and after accelerated conditioning [131-133]. Proposed bond durability factors were similar and were also found to agree well with a database of bond durability test results from the literature [131, 132, 134]. However, more bond durability tests should be conducted on FRP assemblies exposed to different outdoor environments and accelerated conditioning protocols should be adjusted based on outdoor test results if needed.

Research by Karbhari et al. showed that pull-off test adhesion strengths after long-term environmental testing for two years in deionized water, salt water, and 95 % relative humidity had a transition in failure modes from cohesive to adhesive failure or a mixture of both [87]. Moreover, salt water caused a higher level of degradation than salt water in the FRP composite itself and at the FRP composite/concrete bond, possibly due to ingress of NaCl [87]. A > 40 % loss in pull-off bond strengths, more adhesive failure, and some FRP composite interlaminar failure were observed [87]. In a study by Dai et al., wet/dry cycling by immersing FRP assemblies in salt water at 60 °C for 8 months followed by rapid drying was found to drive formation of micro-cracks at the adhesive-concrete interface and led to greater reductions in pull-off bond strengths [135]. Moreover, flexural capacity of the FRP assembly (580 mm for length, 100 mm for width, 100 mm for thickness) decreased after two years while no significant change in ductility was observed [135]. Overall, there were different strength reduction trends for the pull-off adhesion strength and flexural strength of the FRP assemblies and more research is needed to understand their relationships. In a study by Cromwell et al., exposure of FRP assemblies to alkaline conditions for up to 10,000 h to simulate long-term exposure to the high pH environment of concrete, showed bond degradation by short beam tests for GFRP composites, but not for CFRP composites, owing to the known degradation of glass fibers at high pH [132].

The effects of long-term loading conditions on FRP composite bond adhesion to concrete were conducted under static (creep and relaxation), quasi-static (*e.g.*, tensile tests, compression tests, flexural tests, *etc.*), and dynamic (*i.e.*, fatigue) loading conditions in several studies to simulate various loading conditions in the field and a reduction in FRP composite bond strength was observed [80, 125]. Ma et al. also conducted with an acoustic emission technique to monitor damage evolution in FRP assemblies during cyclic loading [136]. Relaxation behaviors were shown to have an effect on the adhesion stress of the CFRP composite/concrete interface investigated at various temperatures (25 °C to 175 °C) by Alqurashi et al. The bond strength decayed exponentially with increasing temperature and the effect was particularly noticeable above 150 °C [137]. Moreover, daily temperature variations outdoors can create mechanical stresses within the FRP assembly. In particular, freeze-thaw cycling can generate the largest mechanical stress on the adhesive layer by the expansion and contraction of entrapped water. Freeze/thaw cycling is typically conducted according to ASTM C666 with a total of 300 freeze/thaw cycles but many researchers selected different cycles for their research, making comparisons of data difficult [138]. Freeze/thaw cycling studies have been conducted on FRP assemblies by Subramaniam et al. using a direct shear measurement and digital image correlation [139]. Compared to control FRP assemblies, a larger percentage decrease in the interface fracture energy was observed along with a decrease in the ultimate load at debonding. The length of the cohesive stress transfer zone and the maximum interface cohesive stress were also found to decrease with freeze-thaw cycling [139]. Other studies have conducted compression testing of FRP retrofitted cylinders after freeze/thaw cycling and found that CFRP and GFRP assemblies experience minimal (≈10 % to 15 %) to significant (> 15 %) reductions in strength and ductility depending on the concrete used [140, 141]. Catastrophic, brittle FRP composite failure was found to occur in some cases [140, 141]. Four-point bending tests, short beam shear tests, and peel tests on FRP assembly specimens have shown no decrease or some decrease in assembly strength depending on freeze-thaw conditions and in some cases an increase in interfacial fracture energy was observed [132, 142, 143]. When assemblies were submerged in a calcium chloride solution by Chaje et al. during freeze-thaw testing, more adhesive failure was observed for all types of FRP composites. Both aramid FRP composites and E-glass FRP composites lost over half of their flexural strength while CFRP composites did not lose much strength [144]. A better understanding of FRP assembly strength loss by freeze/thaw cycling and long-term cold weather exposure is needed to compare fabric durability in cold climates. Furthermore, a comparison is needed of assemblies exposed to freeze-thaw cycling in the laboratory to assemblies exposed outdoors to validate the degradation pathways observed with accelerated conditioning. Not many studies have looked at FRP assemblies under stress or sustained loads while being exposed to environmental conditions such as freeze-thaw or moisture.

Most research is performed using pristine instead of deteriorated concrete as the substrate, thus overlooking a fraction of concrete substrates retrofitted in the field. However, one study by Dai et al. did investigate the application of FRP composites to concrete deteriorated by frost damage. The study found that concrete spalling or covercrete delamination (as much as 15 mm thick of concrete delamination) occurred after static and fatigue testing, with different interfacial bonding strength and stiffness influencing the degree of delamination as a function of the existing levels of damage in the concrete [145]. This implies that the condition of the concrete plays an important role in the adhesion performance of the FRP composite to the substrate and this type of study may be useful after exposure of the FRP assembly to other accelerated conditioning tests. Ultimately, more studies are needed to develop reliable performance criteria for FRP assemblies prepared with deteriorated concrete.

2.3.3. Performance of FRP Retrofitted Structures

This section overviews the state of research concerning the initial and long-term performance of FRP retrofitted structures. Research concerning the initial and long-term performance of retrofitted structurers are further divided into one of three subtopics: experimental studies, *in-situ* studies, and numerical studies. The information provided in this section helps to identify research needs that exist in the literature.

2.3.3.1. Initial Performance Improvement of FRP Composite Retrofitted Structures

<u>Experimental Studies</u>

There have been several experimental studies in the last few decades on the enhancements that externally bonded FRP composites can impart on a structure [23, 146, 147]. These studies showed that application of FRP composites can provide performance improvements including enhanced confinement, load-bearing capacity, blast resistance, and shear resistance, depending on the application to the component. Externally bonded FRP composites have been applied to different structural components such as columns, walls, beams, and beam-column joints for the purpose of repair, retrofit, or a combinations thereof. Research has shown that externally bonded FRP composites have a significant effect on the performance of these components. Cyclic backbone curves, which give the force-deformation relationship of a component based on hysteresis curves from experimental testing, can illustrate the increase in ultimate strength and ductility of retrofitted structural components against elements that were not retrofitted. This section goes into detail about some of the experimental studies involving FRP composite application to structural components and the resulting impact on the initial performance of structures.

External confinement of a column is necessary when a structure is damaged or needs to be upgraded. External confinement can restore or increase the load-carrying capacity, ductility, and energy absorption capacity of the component [23, 61]. The effectiveness of FRP wrap confinement is reduced for columns with square or rectangular cross-sections, because the confining pressure is not uniform and is concentrated in the corners. Practitioners have overcome this issue by creating an equivalent circular or oval shape prior to retrofit or increasing the thickness of the FRP wrap required by design [148]. Different methods have been proposed to circularize a column, including bonding precast concrete to the original column and casting fresh concrete to achieve the appropriate circular or oval design, which increases the effectiveness of FRP wrap confinement [149, 150].

RC beam-column joints can experience poor performance under seismic loading if they are not designed properly. Non-seismic joints often have strong beams and weak columns, inadequate confinement, and other nonductile detailing that can lead to formation of plastic hinges in the columns or shear failure in joints [151]. Retrofitting these components with FRP composites by reinforcing the beam, column or both with full wraps, U-wraps or one-sided layers of FRP composites has been shown to improve the shear strengthening and effective confinement of the joint. This retrofitting technique has advantages over other retrofitting techniques, such as concrete jacketing and steel jacketing which significantly increase the member sizes and are more labor-intensive to apply [151]. El-Amoury and Ghobarah performed tests on GFRP retrofitted RC beam-column joints, with RC beam-column joints representative of those designed before 1970 [152]. The goal of the GFRP retrofit design was to replace missing joint shear reinforcement or inadequately anchored reinforcement. The experimental results indicated elimination of brittle shear failure, improvement of the bond conditions of the top beam reinforcement, as well as improvement of ductility and load-carrying capacity of retrofitted specimens, in comparison with the control specimens. Pantelides, et al. also studied RC beam-column joints that were built before 1970, had little shear reinforcement, and behaved in a non-ductile manner [153]. The FRP retrofit was employed to improve the shear capacity and increase ductility of the beam-column joints. Four layers of CFRP were wrapped around the column and joint in two diagonal directions. The results showed that the retrofit achieved design goals by increasing the joint shear strength by 45 % and the ductility by 68 %. There are several other publications that explore the use of FRP composites to retrofit beam-column joints, but further research is still needed in areas such as the design of anchorage for retrofitting beam-column joints with FRP and the performance of the FRP retrofit under different environmental conditions [154-156].

Existing RC walls, such as those that are under-reinforced or built to an older code without adequate seismic provisions, require retrofit to perform effectively under seismic loads. FRP composites work well to provide shear strengthening and confinement to walls in order to improved performance. While experimental research on this topic has been explored in countries outside of the U.S., experimental research on FRP retrofitted RC shear walls within the U.S. is limited. Mosallam and Nasr explored the retrofit of walls that had post-construction openings installed [157]. External retrofit was required in this case to restore structural integrity of the component and regain the structure's seismic ductility. An FRP retrofit lamination system was designed to include both horizontal and vertical laminates that fit the geometry of each wall specimen. The results of the tests indicated that the FRP was able to restore and enhance the strength and ductility of the wall in comparison to a specimen with openings and without retrofits. Paterson and Mitchell investigated a proposed seismic retrofit of an existing concrete core wall of a building in Berkeley, California [158]. The objective of their experiments was to determine the improvement in ductility and energy absorption of the wall after retrofit with CFRP composites and headed bars [159]. The retrofit design proved effective at reducing the shear stress in the test specimens. The literature shows a need to further investigate the performance of FRP retrofitted walls, in particular existing walls in the US, in order to improve design codes and guidelines related to the retrofit of RC walls using FRP composites.

Often, after a natural hazard, a repair technique is needed that can be implemented rapidly [160]. One of the major benefits of FRP composite use is their effectiveness as a rapid repair system for damaged components. Sun et al. conducted an experimental study that demonstrated the effectiveness of the rapid repair method of damaged concrete piers using early-strength concrete and FRP composites [161]. The study showed that repair with FRP composites changed the failure mechanism of the structure to a more preferred failure mechanism: the repaired piers displayed a ductile flexural failure mechanism, while the original concrete pier displayed a flexural-shear failure mechanism [161]. He et al. studied the rapid repair of severely damaged square columns that had undergone different loading combinations of bending, shear, and torsion [162]. The method of repair included replacing lost concrete with quick set mortar, and application of externally bonded longitudinal and transverse CFRP composites, without repairing any longitudinal reinforcement. Their findings showed that, as long as the longitudinal reinforcement was not fractured, the repair technique was successful in restoring bending or torsional strength. Impact-damaged prestressed concrete beams are other components that need to be repaired to restore load capacity to infrastructure [162]. Other researchers demonstrated the usefulness of CFRP composites for repair with some limitations, including the maximum loss of prestressing force in impact damaged pre-stressed concrete and debonding concerns of the FRP composite from the structure [163-165].

The application of FRP wraps and laminates with FRP anchors has received more attention from the research community in recent years. FRP anchors are used to improve the effectiveness of the retrofit and to delay or prevent debonding of the FRP composite from the structure [50]. Smith et al. tested RC slabs and found that strengthening the slab with FRP composites and installing FRP anchors increased the strength and deflection by 30 % and 110 %, respectively, over the FRP composites reinforced but unanchored to the RC slabs [50]. They also studied the effect of fiber content, placement and spacing of the anchors on the response of the slab [50]. Koutas and Pitytzogia investigated the effectiveness of different FRP anchor configurations for shear strengthening of RC T-beams [166]. Some of the conclusions from this research were that anchors placed inside the slab or flange of the T-beam outperformed anchors placed in the web of the T-beam, and that the performance of anchors made of glass and carbon were similar when placed at the same angle and spacing [166]. Jirsa *et al.* also performed experimental tests on concrete bridge girders strengthened with CFRP strips and anchors for shear [14]. Different beams, such as I-beams and T-beams, were tested using uni-directional and bi-directional configurations of the CFRP strips to compare the performance of these types of configurations. The results showed that bi-directional strips did not significantly increase the shear capacity but did improve serviceability by reducing crack widths and improving stiffness. The use of anchors when retrofitting RC walls is also important. There have been a few studies that investigated the design and performance of FRP anchors used with FRP composites for retrofitting RC walls, such as the study by El-Sokkary et al. [167]. This study looked at two anchor designs for the walls: one-sided fan anchors and through-slab fan anchors. The results showed that the one-sided fan anchor outperformed the through-slab anchors due to unexpected elongation and loss of efficiency during loading cycles. The literature identifies the need for further research on the effectiveness of FRP anchors in terms of their geometric placement and fiber content in the context of component or structural performance.

<u>Numerical Studies</u>

Numerical models are important tools for understanding the effects of FRP retrofit on the behavior of a structure, and also for estimating the response of retrofitted structures. Santarsiero used finite element (FE) modelling with ATENA 3D software* to gain insight into the behavior of wide beam-column joints retrofitted with FRP composites [168]. Using experimental data to calibrate a finite element model and truss elements to simulate the FRP composite mechanical properties, Santarsiero found that as the number of layers of FRP wraps increases, peak load responses increase, but ductility decreases due to debonding [168]. Mahini and Ronagh developed finite element models in the software program ANSYS for retrofitted beam-column joints to determine the effectiveness of CFRP web-bonded systems to strengthen the joint [169]. The researchers found good agreement between the numerical predictions and the corresponding experimental results. The numerical results were able to capture three types of failures of the beam-column joints: (1) flexural failure at the beam-end facing the column, (2) localized beam hinging zone, and (3) distributed beam hinging. The results showed the web-bonded CFRP composite system was effective in controlling the plastic hinge location in RC moment resisting frames [169]. Deifalla and Ghobarah created a model to predict the behavior of retrofitted box beams subjected to torsion, which is a complex problem to solve numerically due to the lack of experimental results that are needed to better understand the response [170]. Their model comprised a set of equations compiled from previous studies that represent material models, equilibrium equations, and assumptions. The model was validated with respect to 20 available experimental results, which included several FRP retrofit schemes for torsional strengthening. The proposed model, when compared to each experimental result had an error ranging from 1 % to 25 % [170].

Modeling parameters used in design standards determine a generalized force-deformation relation for structural components and are used for developing computer models for nonlinear analysis. ASCE 41-17, the standard in the US on evaluating existing buildings, provides modeling parameters and acceptance criteria for several RC components such as beams, columns, beam-column joints, structural walls, and two-way slabs. These modeling parameters are often informed by component level tests and the resulting backbone curves. However, there is a lack of modeling parameters for FRP-retrofitted RC components in the ASCE 41 standard. ACI 440.2R-17 does provide guidance for the design of FRP and ACI Committee 369 is currently working on developing these parameters for retrofitted RC columns so that the parameters can eventually be adopted into ASCE 41 [7]. Incorporating these modeling parameters into ASCE 41 will help practicing engineers determine the expected behavior of FRP-retrofitted structural components and the associated acceptance criteria. Another key issue that needs to be addressed is whether to continue conservatively defining the ductile response of FRP retrofitted components as a force-controlled action.

Modeling repaired structures can present challenges, one of which is capturing the behavior of damaged and repaired materials. He et al. described two procedures that have been used in research to address this issue: the two-phase method and the damage index method [146]. The two-phase method includes elements of the as-built components and repair elements at the beginning of the modeling procedure, with the repair elements being inactive until the second phase when the damaged portions are replaced with the repair elements. This method, therefore, considers the history of loading, damage, and repaired elements explicitly in the method. The damage index method begins with assumptions of a damaged component and starts the modelling procedure at the point of introduction of the repaired components. With this method, material parameters are modified to match the effect of damage and repair [146]. Lee et al. and Duarte et al. have tackled this challenging topic using the two-phase method and damage index method, respectively [171, 172]. Lee, et al analyzed an RC bridge repaired with CFRP jackets using repair elements that had prescribed birth and death times. Depending on the analysis time step, these repair elements would be inactive or active [171]. Duarte et al. employed the damage index method by using a smeared crack model with a higher fracture energy than the undamaged concrete to simulate a beam repaired with epoxy injection and strengthened with CFRP composites. They found a good agreement with these models when compared with experimental data [172]. Despite the advances by some researchers, research on numerical analysis of repaired components is still limited.

The bond between the FRP composite and the concrete substrate is a critical factor for effectiveness of the retrofit system. To address modeling of debonding failures between FRP composites and concrete substrates, Yang et al. (2003) developed a discrete crack model-based finite element analysis method for FRP-plated RC beams that simulated discrete crack propagation until structural collapse [173]. The premature debonding failure mode of the FRP retrofit that was simulated in the computer program was the "pulling-off" of the concrete cover. Their study showed that a beam strengthened with a shorter plate is more likely to fail than one with a longer plate due to concrete cover separation [173]. Chen et al. focused on modelling the intermediate crack debonding, where debonding is initiated at a flexural crack and propagated towards the plate end, between FRP plates and RC beams [174]. To predict the intermediate crack-induced (IC) debonding failure mode, they developed an advanced finite element model using the smeared crack model and a dynamic approach, where a static problem is treated as a dynamic problem and solved using an implicit time integration method in ABAQUS to overcome convergence problems. They showed that their proposed modeling approach provided accurate predictions of the IC debonding failure as well as crack paths and load-displacement responses when compared to the experimental results [174].

Studies on the numerical simulation of FRP retrofitted structures with FRP anchors are limited in the literature. Yang et al. developed finite element models of FRP-strengthened RC slabs with FRP anchors that had been tested experimentally. They developed 2D models in ABAQUS using existing FRP-to-concrete bond-stress models [175]. The numerical models were calibrated using the experimental results. Those anchor models from the validated models were then incorporated into finite element models of joints and slabs. The predicted results compared well with RC slab experimental test results [175]. The limited number of studies on numerical modeling of FRP-retrofitted components or structures with FRP anchors may identify the need for further research on the topic.

2.3.3.2. Long-Term Performance of FRP Composite-Retrofitted Structures

Experimental Studies

Environmental exposure for outdoor applications is a major cause of deterioration for FRP composites retrofitted to structures. The effect of environmental exposures on FRP composites has been the subject of several research studies. Specifically, these studies have exposed FRP composites to UV radiation, alkalinity, salt water, temperature cycles, and freeze-thaw cycles. However, correlating the effect of environmental exposure on FRP composites to the long-term structural performance of the FRP composite structural system remains a challenge, as studies on long-term performance of full-size components or structures are limited.

Including environmental reduction factors in the design process is a typical way to account for expected deterioration of the strength of FRP composites. Guidance on incorporating the effects of environmental exposure into the design process is addressed in Table 9.4 of ACI 440.2R-17, which lists environmental reduction factors that are applied to the strength of the FRP composites used in design calculations [54]. The reduction factors are conservative estimates based on the relative durability of the FRP composites, and no reference to any experimental tests is given as to the origin of these factors. The AASHTO *Guide specifications for design of bonded FRP composite systems for repair and strengthening of concrete bridge elements* states that the FRP composite materials used for strengthening of bridge components must be tested under several environmental conditions to ensure that no condition will lead to a loss of more than 15 % of the glass transition temperature or the tensile strain [10]. Dolan et al. developed a set of experimental test procedures that can provide the data necessary to compute a durability strength reduction factor for an FRP composite system [176]. They looked at two conditions, a wet environment where the specimens were totally submerged in water, and air condition where the specimens were exposed to 100 % humidity. They also suggest procedures for accelerated conditioning and long-term, outdoor exposure. However, these recommendations are limited to only CFRP composite systems that have not been exposed to UV light. Therefore, more research is needed on the calculation of strength reduction factors that can cover a range of conditions.

Due to time restraints, accelerated conditioning is used to simulate environmental exposure of FRP retrofitted structures to understand their effect on long-term structural performance. Different metrics, such as reduction in the confinement of concrete and steel loss or loss of steel reinforcement due to corrosion, are studied to estimate how an FRP retrofitted structure will degrade over time in field applications. Myers et al. performed a series of tests that explored the combined effects of different accelerated conditioning tests, such as wet-dry cycles, freeze-thaw cycles, and UV exposure, on the mechanical properties of FRP-strengthened beams [177]. Aramid, carbon, and glass fibers were tested. Their research showed that, regardless of fiber type, combined environmental exposure has a detrimental effect on the bond performance of FRP composites to concrete structures, indicated by a reduction in flexural stiffness, and that structures carrying a higher sustained load experienced more bond degradation compared to those unloaded specimens [177]. Previous research showed that GFRP composites are vulnerable to wet/dry and freeze-thaw cycling, and confinement capacity columns can be reduced by 18 % to 30 % [143, 178, 179].

Corrosion repairs and future corrosion prevention of internal steel reinforcement are concerns of the engineers when rehabilitating a RC structure with FRP composites. Corrosion is detrimental to a structure, causing steel loss, and internal expansion that can lead to cracks. One desirable quality of FRP composites, as compared to other repair materials, are their non-corrosive nature, and efficacy as a barrier against future corrosion. How FRP-repaired structures perform against corrosion has been the subject of several studies. Berver et al. tested FRP-wrapped RC specimens with exposure to cycles of salt water for up to two years [180]. They found that FRP composites prevent corrosion of internal steel reinforcement below undamaged, uncontaminated concrete. However, their test results showed that FRP composites do not prevent corrosion of internal steel reinforcement under the FRP wraps of contaminated and repaired concrete; they also showed that chloride is able to infiltrate beneath the FRP wraps through adjacent concrete. Berver et al. recommended removing all contaminated concrete prior to repair and sealing areas of concrete most likely to be exposed [180]. Belarbi and Bae performed several tests on small-scale RC columns under ambient environmental conditions and accelerated corrosion conditions [181]. The corrosion tests showed that the FRP wrapped specimen can experience corrosion during the dry stage of wet/dry cycling because of entrapped moisture [181]. Other experimental studies showed that FRP wraps are successful in slowing the corrosion rate of internal steel reinforcement [182, 183].

Field Studies

As stated previously, FRP composites have been used in the field for over 20 years, so there is the potential to learn from these in service FRP composites to understand long-term performance of FRP retrofitted structures. Survey reports give a snapshot of the widespread use of FRP composites for public works but there are few studies that detail or investigate the performance of these systems after multiple years of use [184-186]. Departments of Transportation (DOTs) have the potential to provide a wealth of knowledge, as bridge and other infrastructure inspections occur regularly, and many DOTs have used FRP composites for repairs. Some information on the condition of the FRP-retrofitted DOT structures is available in published research reports [16, 187]. Hamilton et al. sought to determine the change in effectiveness of the FRP composite repair due to real-time exposure of 10 years or more to environmental conditions by testing retired bridge girders that had been retrofitted with FRP composites [16]. One finding from the study is that the majority of pull-off tests met the manufacturer’s specifications, but that many tests indicated an undesirable failure mode, which implies either installation issues or that bond degradation occurred. Another observation from the study was that chloride ion intrusion was reduced in regions with FRP composites compared to exposed areas of the girders, which may indicate that FRP composites can provide modest protection of internal steel reinforcement from corrosion by simply blocking ingress of chlorides. Simpson et al. monitored the progress of cracks four years after the repair of a bridge that was deficient in shear [188]. Through the use of strain gauges, no crack movement was observed and the repair was determined to be successful [188]. The literature review shows that research on the *in-situ* quantification of the long-term response of FRP retrofitted structures is sparse and should receive more attention.

Numerical Studies

Modeling the deterioration of FRP composites and FRP retrofitted structures can inform service life prediction of a structure after the repair is completed. Myers and Sawant developed an interaction model to predict life expectancy of FRP retrofitted bridges based on statistical data [189]. They used data on the corrosion rate of steel before and after retrofit, bond degradation, and degradation of FRP composites to develop an approach to predict the life expectancy of the structure. They validated their model using a Missouri bridge that was retrofitted with FRP composites in 2003 [189]. Not many other research studies that address durability or aging with respect to numerical modeling of FRP retrofitted concrete structures/components are available, so this is an area where more research should be performed.

3. Workshop Summary on Research Gaps in Material Performance of Externally Bonded FR Composites

This chapter examines the challenges and research needs for the performance of externally bonded FR composite materials. Emphasis is placed on materials selection (prior to construction), the initial and the long-term performance of FR assemblies, and the challenges to usage. For an engineer considering FR composite materials for retrofit or improvement of existing construction, reliable information on the materials characteristics and performance is essential to ensure proper calculation of the structure performance. Collaboration of standards organizations and expansion of guidelines and codes will enable more FR composites to enter the market. Furthermore, more practical *in-situ* tests are needed for quality control during construction and the monitoring of long-term structural performance. This section of the report describes the most important challenges that practicing engineers and researchers face to select and characterize the performance of FR composite materials. Research needs are presented here based on feedback from the workshop and are ranked based on the priority (highest, higher, and high) they were given by stakeholders.

3.1. Criteria for Materials Selection

In the planning of any construction project, it is essential that the materials to be used are selected correctly. Improvement of materials specifications and increasing the availability of data would make this process more transparent and allow other FR composite formulations to more easily enter the market. One important issue related to materials selection is what code/standards are needed to ensure the proper selection of the materials. There might be a need to develop new test methods to quantify the performance of new materials as they enter the market. Furthermore, appropriate selection of a substrate for FRP retrofit requires guidance to ensure that the bond is strong and durable.

3.1.1. Development of Criteria for FRP Composite Materials Selection for Non-concrete Substrate (*e.g.*, Steel, Timber) Application (Highest)

The application of FRP composites to timber structural components has been demonstrated but there are not many studies that systematically evaluate the improved performance of FRP retrofitted timber components. FRP composites have also been applied to steel substrates but quality control (QC) of the application process was found to be difficult due to variations in surface roughness, paints, and corroded surfaces. Thus, for both types of substrates, there are potential benefits for FRP retrofits but further research is needed to improve understanding of performance and the selection process for FRP materials, adhesives, primers, and putties.

3.1.2. Evaluation & Combination of Performance Specifications & Test Standards by Neutral Entities (Higher)

Proper materials selection requires clear performance-based specifications. Such specifications need to be evaluated, coordinated, combined, and potentially further developed, possibly by a neutral entity such as a standards developing organization (SDO). These specifications need to include the type of substrate and its status (level of deterioration), as well as criteria for determining the performance of the materials to be considered, such as FRP composite adhesion to the substrate. A specifier needs to be able to compare results from various sources and the results can be comparable only if all materials were tested using standardized test methods. Thus, metrologies for acceptance testing need to be standardized and possibly further developed. The standardization will ensure that the tests are conducted the same way by all evaluators.

3.1.3. Development of QA/QC Metrologies for Evaluation of Materials Selection (Higher)

QA/QC in the field fulfills two important functions: QA defines the processes and tests (*i.e.*, acceptance criteria) used for materials to prevent quality and performance issues, QC tests the quality and performance of materials as they are produced. Thus, to foster the development of new FR composites with a variety of new fibers, mixture of fibers, or polymer matrices, improved or additional performance-based specifications need to be developed. For example, the moisture tolerance of epoxy can vary greatly but there are no specifications of moisture tolerance in specific applications. Furthermore, determining the acceptable concrete substrate quality may require further testing protocols. Overall, there is a need to formulate or improve test methods to have a low coefficient of variation between tests and testing laboratories. Once the specifications and related methodology to test the performance are improved, any composition of FR composites can be tested and evaluated for performance with specific applications or substrates in mind.

3.1.4. Identification of Evaluation Criteria of Materials to Determine Interface Quality Between FR Composites and a Substrate (High)

FR composites are attached to substrates using chemical bonding, physical anchors, or both. The selection of the method is dictated by the application, but in all cases, specifications need to be in place to ensure the quality of the bond. If the bond is not assured, the FR composite cannot be relied upon to provide the needed retrofit/repair performance. Evaluation criteria for saturants, adhesives, primers, and putties bonded to concrete substrates are currently not in place. For example, some epoxies are moisture tolerant while others are not, so some epoxies may be suitable for a given concrete substrate while others may not. The interface quality is also dictated by the substrate quality, which needs to be evaluated or modified using abrasive techniques prior to FR composite attachment. Substrate surface preparation needs may vary depending on the saturants, adhesives, primers and putties, too. Currently, only pull-off tests from a few locations of FRP-retrofitted structures are required to assess the bond strength and this testing is location-specific and not necessarily fully representative of the entire retrofitted area. Overall, more evaluation criteria are needed to ensure the bond between the FR composite and substrate is strong and durable.

3.1.5. Assessment of the Concrete Substrate Condition and Evaluation of its Effect on FR Composite Bonding Properties (High)

The status of the substrate needs to be examined to understand the existing type of deterioration (*e.g.*, damage from the alkali-silica reaction (ASR), freeze/thaw, internal steel reinforcement corrosion, or other) as this can affect the bonding properties with the FR composites. Many types of concrete damage have the tendency to progress in the presence of water/moisture. There is a need to develop a full understanding of how FR composites might affect progression of deterioration mechanisms. For instance, if water is trapped inside a column by an FRP composite, it is conceivable that ASR deterioration will continue, jeopardizing the strength added by the FRP retrofit. Thus, a better understanding of how the existing concrete damage can affect FR composite strength and how the FR composite may affect continued concrete deterioration needs to be further investigated through experimental measurements and models.

3.2. Initial Performance of FR Composite Materials

This section covers material-level research needs regarding initial performance of FR composite materials after installation in both interior and exterior applications. The installation process strongly affects the initial performance of FR assemblies. Thus, how to inspect and to further improve the installation process are important research areas. Research needs include identifying the factors to consider when evaluating FR composite installation, and challenges or improvement needed in codes/standards and test methodology for initial *in-situ* material performance evaluation.

3.2.1. Improvement of Current Test Methods (QA/QC) to Reduce Uncertainty in the Test Results for Determining the Initial Performance (Highest)

Standardized test methods (QA/QC) for field inspection are critical for consistent evaluation of the initial performance of FR composite materials after installation. The most common test method currently used is the adhesion test, or pull-off test, but large uncertainties in test results have been shown without comprehensive data to identify the reasons for high variability in the results. For FRP composites applied to a concrete surface, debonding failure of the FRP composite can occur either through adhesive failure at the interface of the concrete and the FRP composite or adhesive failure (*i.e.*, interlaminar failure) within layers of the FRP composite. If a strong bond is achieved between the FRP composite and concrete, cohesive failure should occur in the concrete substrate. The mode of failure often depends on concrete surface conditions. For design purposes, FRP retrofits meet design guidelines in which cohesive failure occurs at a certain bond strength (> 1.4 MPa or 200 psi) as recommended in ACI 440.2R-17 [7]. This acceptance criterion is considered most important for bond-critical applications such as in shear and flexural strengthening. However, guidance documents are not clear about failure modes for FRP composites in contact-critical applications. For all adhesion tests, an acceptable level of uncertainty and the largest sources of uncertainty in the test are not explicitly provided, nor are the number of tests and locations. Alternative, cost-effective test methods that determine if the FRP composite bond strength is adequate and further guidance to address the high variability of pull-off tests are needed. Guidance is also needed for pull-off tests conducted on FRP retrofitted building components with various geometries. The improvement or identification of practical issues within these test methods could lead to development of more comprehensive inspection protocols. For FRP witness panels sent to laboratories, research efforts to improve test methods/protocols to have smaller variations in test results for better assessments are also needed. Specifically, more guidance and research is needed on preparation techniques for witness panels in the field including the panel substrate, panel size, and comparability to the actual installation; techniques in the lab including curing, cutting, gage length, grip tab type, grip tab preparation, grip tab pressure rate of loading; whether to use the specified thickness or the actual measured thickness; and guidance on expected statistical dispersion of results.

3.2.2. Identification of Criteria for Application of FRP Composites to Non-concrete Substrates (Higher)

The bond between FRP composites and the surfaces of steel structural components significantly influences the load-bearing capacity of the retrofitted structure. If FRP composites are applied to a steel structure, bond behaviors can be different than for FRP composites applied to concrete due to the intrinsic differences between concrete and steel. Future research should be conducted on bond strengths of FRP composites to steel to help develop acceptance and design criteria for this type of application. It is difficult to control the surface conditions of steel. Furthermore, steel is often protected by paint but concrete is not, and metrologies to assess various surface conditions (*e.g.*, surface roughness, painted and corroded surfaces) are crucial to ensure an optimal bond with the steel surface, especially since the bonding strength is related the surface treatment. Specifically, research is needed to understand the bonding between painted and untreated steel surfaces and test methods are needed to qualify substrate surface properties to ensure adequate bond strength. Currently, there are no non-destructive evaluation (NDE) test methods for measuring bond strength during installation, especially for FRP composites applied to painted and untreated surfaces.

3.2.3. Development of Guidelines to Address Specific Geometric Issues During Application (Higher)

Guidelines are needed to specify requirements for application of FRP composites to substrates with different geometries. For example, uneven surfaces and different geometries can receive different coverage of resins than other areas and therefore lead to less strengthening in these locations. This can cause moisture/air entrapment that eventually leads to debonding issues.

Engineers need some basic geometric guidance on how much gap area of exposed substrate between FRP saturated fabrics is acceptable to prevent potential moisture entrapment.

3.2.4. Development of Metrology to Measure the Saturation Level of Resins (Higher)

The ratio of FRP composite fiber to resin in application can affect the bonding between the FRP composite and substrate. It is important to assess the amount of FRP composite fiber versus the amount of resin during the installation. Research is needed for the development of an *in-situ* method/metrology to characterize the saturation level of resin with respect to fibers at the installation site to measure voids that can trap moisture or otherwise lead to debonding. Currently, witness panels sent to laboratories from the field are only tested for degree of cure, mechanical properties, and glass transition temperature [7].

3.2.5. Input of Parameters from Initial Installation for Improved Numerical Modeling (High)

Improvement of numerical modeling techniques for FR composite retrofits can be accomplished using input from installation measurements currently used for QA/QC such as bond strength, moisture content, tensile strength from pull-off tests, and other important properties. Furthermore, to predict the long-term performance of FR assemblies, the data from initial installation measurements can be used. This information is critical as a baseline for monitoring the FR composite bond strength and fatigue over the lifetime of the structure.

3.3. Material Degradation During Service

FR composite assemblies in the field are exposed to various environmental conditions such as moisture, high and low temperatures, UV light, alkaline and acidic conditions, saltwater, freeze/thaw cycling, and mechanical fatigue/creep. The durability of FR assemblies is affected by constituent material degradation and bond degradation between the FR composites and the concrete substrate. Degradation of FR assemblies can create unexpected loss of structural integrity in retrofitted components and structures. In this subtopic, the most common material degradation behaviors in field applications are discussed along with the specific materials properties and challenges for maintaining long-term performance of FR composites.

3.3.1. Establishment of Correlations Between Laboratory Accelerated Conditioning Test Results and Field Exposure Results (Highest)

Durability data for FR composites and FR assemblies can be collected using controlled laboratory tests that simulate environmental conditions, often in an accelerated way. However, there is a level of uncertainty to connecting the durability data of laboratory tests to conditions experienced by FR assemblies in the field due to the unpredictable behavior of outdoor conditions. Furthermore, accelerated conditioning protocols must be representative of outdoor conditions to not induce degradation mechanisms that will never occur in the field. It is also important to correlate accelerated conditions to outdoor conditions to understand how much faster degradation by accelerated conditioning is compared to outdoor degradation. Specimens for accelerated conditioning may need to be scaled to size, have multiple FR composite layers, and be weathered in different configurations to truly represent field test conditions. Furthermore, environmental durability of FR composites in the field includes simultaneous mechanical stress factors such as fatigue and creep stresses; the FR composites should also experience similar stresses during simulated environmental exposure in the laboratory. Detailed studies on the impact of multiple combinations of environmental conditions on the FR composites should be considered.

3.3.2. Establishment of Inspection Protocols and Indicators of Degradation (Highest)

In addition to post-installation inspection, inspection of FR composites over the lifetime of the structure is important to ensure integrity of the retrofitted structure. Current inspection methods of FR composites and the underlying structure do not adequately identify the rate of degradation. Inspection protocols and test methods are not highly developed for use in the field. Pull-off tests are recommended after FRP composites are out in the field over the long-term, but there is no existing guidance on acceptable pass/fail criteria for pull-off tests conducted as part of inspections. In the case where the underlying concrete degrades over the long-term, it is unclear when an FR composite has to be removed to repair the concrete. In addition, methods to inspect retrofitted elements that are exposed to possible vehicle impact need to be developed. Pass/fail inspection protocols are needed that detect the status of chemical and physical degradation. Ultimately, test methods and inspection protocols need to provide clearer guidance on when FR composites need to be removed and replaced.

3.3.3. Identification of Bond Degradation Mechanisms between FRP Composites and Substrates in Various Environments (Highest)

The bond between a FRP composite and an underlaying concrete substrate is an important parameter because it influences the load-carrying capacity of a component. Deterioration of the bond due to sustained loading and variable environmental conditions is difficult to monitor during the service life of retrofitted structures. Environmental conditions include wet-dry cycles, freeze-thaw cycles, temperature extremes, prolonged exposure to different chemicals, and salt intrusion for FRP composites applied in a marine environment. Degradation of the concrete substrate can also occur and affect the bond between the FRP composite and the concrete (calcium leaching and ASR). The initial curing conditions such as concrete surface preparation, moisture content of the concrete, the mixing and application of resins in an efficient and consistent manner, and weather conditions at the time of FRP composite application can all have effects on the adhesion of the FRP composite both initially and over the long-term. The influence of concrete moisture, relative humidity, rain, temperature and temperature swings, and presence of voids during and immediately after installation may influence bond degradation. Thus, accelerated conditioning of FRP composite specimens with different cure conditions would help better understand long-term performance issues. Detailed research is needed to improve understanding of common bond degradation mechanisms and provide guidance on test methods to assess bond degradation, possibly on the FRP composite-concrete bond in pull-off test samples from inspections. The overall goal is to quantify the remaining service life of the structure.

3.3.4. Development of a Database to Document Degradation Mechanisms in Field Applications (Higher)

Over the past few decades, cases of FRP composites installations were reported by private sectors as well as departments of transportation in various states (particularly CalTrans, FL, TX, VA). Data on the field application of FR composites, by federal or private sectors, can be collected to establish a historical performance database of constituent materials; this database would provide durability information on FR assemblies with respect to various local field conditions, and can be used by material manufacturers and researchers.

3.3.5. Development of Laboratory Tests of FRP Composites with Through-thickness Reinforcements (High)

To ensure long-term performance of FRP retrofitted columns, durability of the constituent materials in FRP composites is important, including additional reinforcements to FRP composites using fasteners (*e.g.*, screws, nails). Among several types of through-thickness reinforcements, shot pins are most commonly used to mechanically attach FRP composites to concrete substrates. Since shot pins penetrate through the thickness of FRP composites, detailed measurements of the damage level of fibers parallel to the main loading direction need to be carried out under various loading conditions including cyclic and gravity loads. Furthermore, research is needed to define locations and spacings for which shot pins cannot be used due to design requirements. Guidance is also needed on mitigating galvanic corrosion of shot pins in contact with CFRP composites. This research need may extend to other through-thickness reinforcements or disruptions, such as anchors, drilled dowels, nails, and penetrations for piping and conduit.

3.3.6. Establishment of Outdoor Exposure Sites and Protocols for Long-term Durability Studies (High)

Laboratory accelerated conditioning requires validation from long-term durability tests conducted in the field. The long-term durability tests in the field are very time consuming for assessing the service life of FR assemblies, so not many outdoor exposure studies have been conducted. Furthermore, the availability of existing durability data from field testing is currently limited. For outdoor exposure experiments, systematic selection of relevant exposure conditions for samples in the laboratory and simultaneously exposure of the same samples outdoors are needed to improve understanding of long-term durability in the field. In addition to laboratory accelerated conditioning protocols (*e.g.*, AC125), test protocols for systematic long-term durability studies outdoors need to be developed to increase the amount of outdoor data available to stakeholders.

3.4. Challenges in Usage

FR composites have been used in civil infrastructure for more than 20 years but use of FR composites to retrofit concrete structures still presents many challenges. This section covers common challenges facing the FR composite industry including improvements needed to current procedures for FR composite installation, metrology needs to ensure proper installation, and coordination issues.

3.4.1. Development of Guidelines and Certifications for Installations (Highest)

Proper installation of FR composites is important to impart the designed structural performance to retrofitted components and structures. The installation quality significantly depends on the installers, so workmanship is a major factor. Although a limited number of training courses are available, establishing a widespread certification program for multiple installation steps that include surface preparation, mixing, and process control for installation schedules can provide improved guidance for installers. Appropriate SDOs can contribute to developing such training courses and certification programs. In addition to installation, training on detailed inspection procedures to verify a proper installation is also important. In terms of inspection guidelines, debonded regions between the FRP composite and the concrete substrate, which affect structural performance, are difficult to inspect because these regions are covered by FRP composites. Non-destructive test methods are already used for conventional construction materials such as concrete (*e.g.,* ASTM C215-14) but developing non-destructive inspection procedures to examine the detailed FRP composite bond regions can improve verification of the installation status and supplement adhesion strength obtained from destructive tests such as the pull-off test (ACI 440.2R-17).

3.4.2. Development of Metrology for Fire Rating of FRP Composites (Highest)

It is well established that the mechanical properties of polymeric materials used in FRP composites deteriorate with increasing temperature. A glass transition temperature is commonly taken to be the critical temperature at which mechanical changes occur, and glass transition temperatures of polymer materials used in infrastructure applications are typically around (104 to 140) °F [(40 to 60) °C] and usually below 200 °F (94 °C). At the much higher temperatures experienced in a fire, deterioration of FRP composite performance will occur. Although fire resistance, smoke density, and fire spread for structural components and materials is evaluated by standardized test methods such as ASTM E119 and ASTM E84, these methods were originally developed for steel, concrete and timber components [110, 190]. Applying current fire codes and standards to FRP composite retrofitted structures is difficult due to potentially different fire test conditions. For example, FRP composites can be flammable and FRP composites can also fall off during a fire. Furthermore, guidelines on the use of fire-proofing materials and intumescent additives, or fire-resistant additives, are needed to incorporate fire safety into design and improve adherence of FRP composites to structures during a fire. Developing fire test metrology for assessing the failure criteria of FRP composites and its consequences on the structural performance need to be considered to improve current codes and standards.

3.4.3. Development of Round Robin Tests and Establishment of Improved Correlations between Small-scale and Structural-scale Tests (Highest)

Small-scale laboratory tests are often used to evaluate structural performance of FR composites including environmental durability testing, but data variations among mechanical, seismic, and durability tests present a challenge for data comparison since test equipment and procedures vary widely. To overcome these obstacles, establishing round robin tests can improve understanding of the reproducibility of small-scale test results. Furthermore, small-scale tests need to be validated by structural-scale tests with a high correlation. Although the structural-scale tests are difficult to perform due to high costs, an increase in the number of datasets obtained from structural-scale tests can improve correlation between the small-scale tests and structural-scale tests. Highly correlated datasets can also validate extrapolation of small-scale results to multiple scales.

3.4.4. Facilitating Harmonization of Specifications and Test Methods Among Various Standards Developing Organizations (SDOs) (Higher)

Various SDOs provide specifications and guidelines for FR composites retrofit designs. To avoid confusion provided on similar subjects, active interactions between organizations are needed. A neutral committee or entity can motivate communication among the engaged organizations not only at the materials level but also at the structural design level to facilitate harmonization of specifications and test methods.

4. Workshop Summary on Research Gaps in Structural Performance of FR Composite Retrofitted/Repaired Structures in Response to External Loadings and Environmental Impacts

This chapter is about understanding the performance of structures that have been repaired or retrofitted with FR composites. This topic includes the performance of the structure under various external loads as well as the effects of environmental conditions on the structure. This topic was further explored in three subtopics: the initial performance of structures, the long-term performance of structures, and the design considerations and standards needed for better understanding and practice. This topic is important because of the expected expansion in use of FR composites for the repair and retrofit of structures. FR composites have the potential to become a more widely used material and the technique of strengthening structures with FR composites could lead to longer use of structures and safer buildings and infrastructure. The value of exploring this topic is to enumerate all of the challenges that engineers and practitioners may face in adopting this repair and retrofit strategy. There are many areas of concern regarding the use of FR composites by engineers and practitioners, including the long-term durability of FR composites, quality control of installation, and education of engineers on the use and design of FR composites in repair strategies. This chapter details the research needs and challenges, gathered from the workshop presentations and group discussions, related to understanding the performance of FR composite retrofitted structures.

4.1. Initial Performance of Structures

Research within this subtopic focuses on developing the resources to understand the initial performance of a concrete structure retrofitted or repaired with FR composites. Initial performance refers to the condition of the structure at the time of the retrofit. This considers the condition of the structure prior to retrofit, including the age and possible damage to the structure. This subtopic discusses what experimental research is needed to improve understanding, what challenges there are in simulating the response of structures, and what numerical capabilities are needed to overcome the challenges. Recommended research needs are summarized in the following sections.

4.1.1. Testing at the Structural-Scale (Highest)

Much information can be discovered from structural-scale testing. Phenomena that cannot be determined from testing small or material-level samples can be determined from structural-scale testing, and it can provide insight into the behavior of structures in the field. Structural-scale testing of components, such as those sponsored by the Texas Department of Transportation [14], have provided useful information about the effects of different FRP composite configurations on structural components. Results from structural-scale testing can also help investigate test size effects and dynamic loading effects. For example, testing of structural-scale diaphragm components is rare, partially because of the difficulty in configuring the test setup. However, testing FRP retrofitted diaphragms would greatly increase understanding of how the performance of these components improves with FRP retrofitting. FRP retrofitted diaphragm tests would also be useful for determining the effects of dynamic loading on performance. Thus, the need for more structural-scale testing, on components such as diaphragms as well as structural assemblies, is an important research need. Information from experimental testing can provide data for better models, better design standards, and better testing standards (*i.e.*, ASTM standards).

4.1.2. Improvement of Numerical Models (Higher)

Numerical models allow engineers to simulate different loading scenarios and estimate the response of a structure to these loads. Accuracy in modelling, from the material level to connections and components, is crucial to being able to accept the results of numerical models. A major research need is the improvement of numerical models, including the need for more accurate models of joints and connections, an accurate depiction of anchor behavior, and models of the bond that include cyclic degradation.

4.1.3. Testing of the Initial Bond of the FR Composite (Higher)

The bond between the FR composite and the substrate is one of the most important aspects of the retrofitted structure. The bond needs to perform well for the structure to achieve the desired performance. Research needs include performance quantification of resins and adhesives and baseline characterization of the FR composite and bond for proper assessment of initial structural performance (see 3.2.1). The relationship between the initial bond and structural performance require further evaluation.

4.1.4. Improvement of the QA/QC of the Installation Process (Higher)

The initial performance of a FR composite retrofitted structure is dependent on the proper installation of the FR composite system. Improper installation techniques or insufficient QA/QC processes can lead to a deficient system at the beginning of the retrofit. Implementation activities related to improving the initial performance of structures include development of certifications for installers of FR composites and development of tools that can assess the quality of surface preparation prior to installation. The need for this implementation activity was also discussed in the material level research needs in Chapter 3.

4.1.5. Development of Non-destructive Techniques to Provide a Baseline for Structural Health Monitoring (High)

Non-destructive techniques are an important way to quickly assess the condition of a building with minimal disturbance to the structure or the occupants. Non-destructive techniques can also provide baseline information from which one can track changes to assess the condition of a material or structure over time. Having the ability to track changes over time can assist with code provisions that give safety factors due to environmental factors and allow for modification of modeling parameters to account for material properties over time. There is a need to develop more non-destructives techniques that give useful information about the structural condition of the FR retrofitted system both at installation and over time.

4.1.6. Improvement of the Understanding of FR Composite Applications for Different Structural Configurations (High)

FR composite application has been studied for several types of configurations, such as round and square column confinement, flexural beam reinforcement, and wall strengthening. There is a need to study the application and performance of more structural configurations retrofitted with FR composites, such as rectangular columns with large aspect ratios, connection or beam-column joints, and more wall configurations, including retrofits that are one-sided versus two-sided retrofits. There is limited testing information about these structural types available in non-proprietary formats (*i.e.*, testing information that is available to the public). The use of FR composites for shear transfer or as collectors between walls and diaphragms, including external FRP composites and FRP anchors, is another area where only limited non-proprietary testing data is available. Experimental testing and numerical modelling are needed to gain more knowledge on these topics.

4.1.7. Development of Better Test Protocols for Characterizing *in-situ* Performance (High)

Test protocols are currently being used in the field to assess the condition of FRP retrofits. These protocols include pull-off tests to assess the bond quality and tensile tests of strips cut from FRP composite witness panels. These testing protocols do not necessarily give the structural engineer the information needed to quantify the performance of the structure in the field. For example, the current testing protocols do not characterize the rate of bond degradation, only the delamination that is or is not present. Research needs include development of better test protocols of the bond and anchorage systems that provide an initial performance quantification of the structure.

4.2. Long-term Performance of Structures

Long-term use of FR composites requires an understanding of a retrofitted structure's performance over time. FP retrofitted structures have the potential to age in various ways that can adversely affect a structure's integrity. Aging can result from multiple environmental factors that lead to FR composite degradation and decreased FRP composite bond adhesion. Furthermore, the effect of applied loads to the structure over time and the occurrence of acute events such as earthquakes will likely change the structural performance. In older buildings and infrastructure, the structural component retrofitted or repaired with FR composites may undergo continued deterioration that also affects the long-term performance of the structure. Since many FR retrofitted structures may be used in the field for 10 or more years, good practices, instrumentation, and selection of the most relevant material property changes to measure are important for assessing how the structure's performance has changed. This section outlines experimental and numerical research needs for structural performance assessment and modeling over time that account for both chronic and acute aging effects.

4.2.1. Improvement of Inspection Practices (Highest)

Improvement of existing practices and development of new practices to inspect FR composite retrofitted structures over time are needed. Inspection practice research needs can be split into two categories: 1) guidelines for inspectors and 2) measurement science tools needed for *in-situ* field testing or post-evaluation assessment of structural performance changes.

For inspectors, improved and standardized guidelines to assess performance changes of FR composites over time are required. This requires consistent certification of inspectors and availability of guidance documents or checklists for the inspectors to follow while in the field. Lessons can be learned from installers of epoxy-grouted anchors [191]. Guidance should be provided on the timing of FR composite retrofitted structure inspections, how to visually inspect them, and what standard inspection measurements to employ. Furthermore, guidelines for post-event evaluation, such as after an earthquake, collision, or fire, should be developed as they do not yet exist.

Standard inspection measurement tools should ideally be non-destructive but can include destructive measurements if done in strategic, non-load bearing regions of the structure. Measurement tools for *in-situ* field testing or post-event assessment, such as non-destructive evaluation (NDE) using infrared thermography and ultrasonic pulse techniques might be useful but require further field and laboratory testing. NDE development is important because the FR composites can hide some of the transformations that occurred to the structural element and adhesive over time. Destructive measurements such as the pull-off test could continue to be employed for assessment of bond degradation with further guidance on selection of strategic, non-load bearing locations of a structure to be tested. Many measurement tools are already available, but inspection protocols have not been developed or employed for adequate use of these measurement tools in the field. Furthermore, documentation of the initial environmental conditions under which the FR composite was applied is not yet part of any inspection guidelines and this lack of records can hinder long-term performance assessment. Overall, test procedures and types of measurement tools should be prioritized along with guidance and certification provided to inspectors.

4.2.2. Development and Validation of Models that Consider Aging and Accumulation of Damage from Minor Events (Highest)

Structural performance models that incorporate chronic events from environmental aging and cumulative damage from minor applied loads require development. First and foremost, these models can help predict the service life of an FR retrofitted structure in the field to prevent structural failures. Second, damage accumulation can be incorporated into models that evaluate structural performance in the presence of an acute, single occurrence hazard event. Third, these models can help inform design, which is discussed in the next section.

Models for long-term structural performance can be based on models currently available for initial performance. Cumulative damage can be incorporated into long-term performance models by aging of FR composite retrofitted structural components in the laboratory using accelerated conditioning tests that are relevant to conditions experienced by the structure in the field. Combinations of environmental factors need to be considered in models and a database of experimental accelerated conditioning data would be useful. Measurement protocols that assess degradation based on structural performance must be employed (*i.e.*, tensile and compressive strength tests). Currently, researchers are not able to capture anchorage and bond performance loss in models, which would need to be specific to structural configurations. Furthermore, characterization of FRP laminate degradation to indirectly assess structural performance requires further research.

Once models are produced with accelerated conditioning data, they should be validated with field data. After validation of these models, a better understanding of how structures will perform following a large hazard event, such as an earthquake, can be determined with consideration of chronic damage that occurred to the structure from dynamic loads and environmental aging. Lastly, these models could help develop performance reduction factors for design based on validated numerical models.

4.2.3. Improvement of Environmental Reduction Factors used in Design (Higher)

During the design phases for a building, multiple aging factors (including environmental and cumulative damage from dynamic loadings) can be incorporated into the design to ensure that the aged structure performs at a particular level for a specified period of time. These reduction or knockdown factors have been determined for certain environmental aging conditions for FRP composites alone but should also be considered with more relevant types of FRP composite-concrete assemblies. More understanding of how these reduction factors are determined, how multiple aging factors should be measured and used in design and further improvements, validation, and consistency in reduction factor determination should be sought. Furthermore, there should be flexibility to alter environmental reduction factors as individual situations dictate.

4.2.4. Validation of Accelerated Conditioning Protocols using Decommissioned Field Structures (Forensic Analysis) (High)

Following from Section 3.1.2, guidelines and measurement tools used to assess performance changes of FR composite systems after application of accelerated conditioning tests should be validated using decommissioned field structures retrofitted with FR composites. Furthermore, the guidelines for working with decommissioned field structures retrofitted with FR composites should require a baseline sample (FR composite + structural element) that was stored under controlled conditions. The data obtained from decommissioned field structures retrofitted with FR composites should then be used to validate models developed from accelerated conditioning tests.

4.2.5. Development of Performance-based Design for FR Retrofits (High)

In structural engineering, structural design has shifted from prescriptive to performance-based in many cases. Prescriptive design is more conservative and often less cost-effective. There has been a push in recent years to move towards performance-based design due to its capability of examining the response of a building with respect to a specific performance criterion. For example, the ACI 440.2R committee has begun efforts to bring performance-based design techniques to FRP retrofit design. One goal of developing and implementing this design method is to better anticipate the expected performance of the FRP retrofitted structure and to avoid overdesign or unnecessary use of FRP, which could improve performance and reduce costs. Further efforts should be made to develop performance-based design approaches for FR retrofits and these performance-based design approaches should incorporate durability.

4.3. Design Considerations and Standards

Research and implementation activities within this subtopic focus on developing technical design and evaluation criteria, guidelines, and standards to design retrofit systems and evaluate the performance of retrofitted structures over time. Developing design guidelines and standards is challenging because fundamental research is needed to improve understanding of the immediate and long-term performance of retrofitted structures. Moreover, development of accurate yet simple models is needed to design retrofit systems. The current Performance-based Seismic Design (PBSD) standards currently lack enough information required for the design of retrofit systems for concrete structures. Moreover, in some cases, there are multiple guidelines published by different SDOs that may not necessarily align. In addition to the development of standards, the implementation and adoption of new standards is an ongoing challenge that needs to be addressed.

4.3.1. Development of Design standards and Guidelines (Highest)

Standards exist for evaluation of existing buildings (*e.g.*, ASCE 41) and design and construction of externally bonded FRP composites (*e.g.*, ACI 440-2R). However, these standards lack critical information required for design of FR composite retrofit systems. There is a great need to develop guidelines on detailing requirements and design of FRP retrofitted components such as anchors [48, 50]. Currently, ACI 440.2R-17 doesn't provide design guidelines for different anchor types, like whether to anchor, what type of anchor to use, or the proper spacing of anchors. However, the document acknowledges the benefits of using anchors, such as delayed delamination and increased effectiveness of jackets, and the use of anchors is widespread as was revealed in the workshop discussions. The development of standards regarding the design of FRP anchors is an urgent need that is being addressed by an ACI 440 task force. In addition, guidelines and standards should be expanded to provide guidance on the backbone curves of retrofitted structural components and the use of FRP composites for new construction. Engineering practice can greatly benefit from inspection and installation guidelines to improve the installation quality. There is also a need for coordination between different SDOs including ACI, AASHTO, and IBC to improve the knowledge transfer between these organizations.

4.3.2. Experimental Research on FR Composite Retrofitted Structural Components and Buildings (Highest)

Experimental studies are needed to improve understanding of the response of FR composite retrofitted structures and to provide the knowledge required to improve the design and evaluation standards and guidelines. Potential experimental studies include testing of shear walls strengthened for shear response with FR composites in different configurations, testing of FR composite retrofitted shear walls with and without anchors, low-cycle fatigue testing of FR composite systems solely and in conjunction with structural components, testing of the shear friction performance of FRP precured dowels, testing of retrofitted RC components with low (less than 17 MPa) and high (more than 17 MPa) concrete strength, and testing of diaphragms retrofitted with FRP composites, including collectors and chords. The use of different loading protocols such as torsional loading protocols as well as more seismic tests on shake tables are needed. In addition, more experimental testing of anchors in different configurations is needed to further update the design guides that are currently under development by the ACI 440-F sub-committee. The experimental research should also include structural-scale testing at the component, subassembly, and system levels. Moreover, experimental data is needed for the response of components up to the failure point to improve the reliability of collapse analysis.

4.3.3. Improvement of Numerical Models for Design (Higher)

A key step towards designing a retrofit system or evaluating the performance of a retrofitted structure over time is development of numerical models. To enable an accurate response assessment of retrofitted structures, numerical modeling capabilities of FR composite retrofitted structures need to be improved. This effort includes development of new models as well as enhancing the existing ones for initial and long-term performance assessment of structures. There are different modeling techniques with varying degrees of approximation and complication. The more sophisticated numerical models that have been developed in recent years commonly require multiple input parameters that are not easily available and usually require testing results. Research is needed to develop the required input parameters for these models. There is also a need to improve the simplified modeling techniques as they are widely being used by practicing engineers as well as researchers. The existing modeling approaches need to be calibrated with respect to the system-level structural response to benchmark the capability of these models to predict what happens in the field or in a structural-scale test.

4.3.4. Development of Backbone Curves using Experimental Data (Higher)

Incorporation of experimental data is an important key to developing accurate yet simple numerical models. These models should be able to capture the key characteristics of the component response. One of the most common modeling approaches used in PBSD is a lumped plasticity approach in which the nonlinear response of a structural component is defined as a set of multi-linear force-displacement relationships (*i.e.*, backbone curves) and assigned to single or multiple springs. The backbone curves, which are derived from experimental data of component responses under monotonic or cyclic lateral loads, represent the response characteristics of the component including ultimate strength, hardening, and softening response, in addition to the hysteretic and deterioration properties. Currently, the main standard for retrofitting existing buildings, ASCE 41, does not provide backbone curves for FRP retrofitted components but there are working groups addressing this issue [192]. Research is needed to develop backbone curves for different retrofitted components using the available experimental data or by conducting new experiments.

4.3.5. Database of Experimental Results (High)

Experimental data on the performance assessment of FR composite retrofitted components and structures need to be collected in a data repository. The database should include testing results for different structural components under different loading types and protocols. Experimental data from other countries should also be integrated into this database. Moreover, a database should be developed that summarizes the influence of environmental impacts on the response degradation of structural components over time. These databases can be used to develop, calibrate, and validate numerical models that assess initial and long-term performance of structures both at the component- and system-level.

4.3.6. Implementation and Adoption of New Standards and Methods (High)

New technologies, materials, or standards will not benefit the public unless they are adopted by the community. There are multiple challenges to adopt a new method or material in design. A key challenge is the potential high cost of the new materials or technologies. An example is the lack of wide adoption of a laser scanning device to measure surface roughness due to the cost of the device. Another key challenge is the potential complexity of new methods or techniques. In addition, the unfamiliarity of engineers with the background and implementation of new techniques may cause a lack of interest to adopt the state-of-the-art methods. These challenges can be addressed by developing practical, low-cost inspection and assessment tools and simplified methods to assess the performance of retrofitted structures. In addition, providing training to engineers can expedite the adoption process of new techniques.

4.3.7. Development of Lifecycle Modeling and Decision-making Tools (High)

Considering the recent advancements in the field of FR composite manufacturing and application, the assumptions regarding the lifecycle cost of FR composites may be outdated and need to be revisited. The lack of guidance regarding the appropriate time for replacing the FR in retrofitted structures is also a challenge especially for practicing engineers, building owners, and manufacturers. Moreover, estimation of the lifecycle cost benefit of FR composite systems using innovative materials is still a remaining challenge. Research is needed to develop new models to evaluate the lifecycle cost of retrofitted structures. A key step for developing these models is to collect required data on the lifecycle cost of FR retrofit systems. The lifecycle models should be implemented in decision making tools that can inform stakeholders on the benefits of the retrofit system as well as the timeline for replacing the retrofit system.

4.3.8. Development of Reliability-based Design Factors (High)

Design factors, or phi factors, are used in the design process to reduce the calculated capacity of the structure. This, along with overestimating the expected demand or loads, is designed to address the uncertainty in the design process with regards to what the structure will experience in the field. There is a research need to develop these design factors using reliability-based methods. The research need is to use experimental test data that consider the combination of environmental effects and loading situations along with probabilistic analysis methods to produce factors with less uncertainty than the factors in use today.

5. Conclusion

5.1. Summary of Research Needs for Stakeholders

The use of FR composites in civil engineering and construction practices has increased in the past 20 years, particularly for the repair and retrofit of existing structures. Despite the extensive prior research conducted on various properties of FR composites at the materials and structural scales, further research is needed to improve understanding of the performance of structures retrofitted with FR composites. This includes improvement in measurement science as well as development of more guidelines and standards to help with selection of materials, understanding the initial and long-term performance of materials and retrofitted structures, and development of codes and standards.

This section summarizes the highest priority research needs identified by stakeholders at a workshop held at NIST in May 2018. Based on the number of votes received for each research topic, the research needs were grouped into three priority groups: Highest, Higher, and High. Three priority groups were determined since the number of votes received for each research need clustered into one of three distinct vote number groups. The assigned priority groups for each research need can be found in Chapter 3, Chapter 4, and Appendix A.

A literature review was also conducted to: 1) provide an overview of the state-of-research concerning FR composites, and 2) develop the framework for the workshop. The workshop discussions and ranking process highlight the research needs with the highest potential impact on the state-of-practice. The highest ranked research needs are summarized in the following sections and further detail can be found in Chapters 3 and 4.

The highest priority research needs summarized in this chapter serve as a roadmap to inform the diverse research plans developed by stakeholders that include NIST, other government agencies, universities, private companies, and other organizations, concerning the use of FR composites for repair and retrofit of buildings and infrastructure. A few research needs identified in the literature but not discussed at the workshop are also provided in Section 5.2. Research studies based off of this report would be most impactful if they apply to relevant structures and common retrofit situations, if design equations accompany research recommendations when possible, if a means for comparing similar retrofits designs is made possible by research, and if design methodology, testing and construction techniques are practical to the construction industry. Further investigation of the outlined research needs by stakeholders will ultimately help develop and enhance FR composite performance and the state-of-practice for our nation's building and infrastructure envelope.

5.2. Summary of Research Needs from the Literature

The research needs identified from a comprehensive literature review are summarized below and are grouped into two main categories: materials and structural levels. The research needs identified in the literature were used to organize the subtopics within the materials and structures topics at the workshop. The materials level subtopics include material selection, initial and long-term performance of FR composites, and challenges in usage of this material. The structural level subtopics include the initial and long-term performance of retrofitted structures and the required improvements in design and standards concerning usage of FR composites.

5.2.1. Materials Level Research Needs:

- Research is needed to assess the impact of installation conditions on bond degradation behavior.
- Development of optimal metrologies to assess status of concrete surface conditions for bonding FR composites are needed, including the use of pull-off tests.
- Not all measurements that assess the initial FRP composite properties are standardized and those that are may require more detail.
- FRCM composites lack design standards and standardized test methods for testing the mechanical behavior. There is also a lack of production technologies to create uniformity in production.
- FRCM composites using inorganic matrices may be a logical choice in harsher environments, but more work is needed to improve bonding between fibers and matrices.
- FRP composites can also be used to retrofit structures made of other materials, such as steel and timber, but there has been relatively little research investigating this usage, compared to the use for RC structures.

- For use of FRP composites on steel, research such as improvement of steel surface treatment, selection of adhesives, and understanding of bond-slip behavior, is needed to increase the acceptance of this retrofit technique
- Research is needed to investigate the long-term performance of FRP-timber systems, like durability, fatigue and creep.
- The lack of usable durability data or access to data is a concern for structural engineers.
- Interrelations among environmental degradation processes at multiple length scales and loading modes needs further study.
- Many durability studies have been conducted on FRP composites and some on FRP assemblies, but not as many studies have examined FRP composites/FRP assemblies under stress while being exposed to environmental conditions.
- Long-term durability data from the field is sparse. Very few studies have comprehensively investigated outdoor degradation of FRP composites due to the long time (*i.e.*, years) it takes to degrade polymeric samples outdoors. Thus, further experimental research is needed on outdoor degradation of FRP composites.
- The issue of scaling accelerated conditioning test data to real time outdoor degradation data adds uncertainty to estimating the service life of FR composite systems without field data.
- There is still uncertainty in experimental data and models for predicting the effective lifetime of FRP composite bonds.
- Aging times and conditions vary significantly in many studies and increased consistency in experimental results could improve understand of FRP assembly degradation. Realistic accelerated conditioning tests that are shown to mimic outdoor conditions are also needed.
- Development of cost-effective and efficient/handheld *in-situ* techniques (*e.g.*, ATR-FTIR, Raman, acoustic, laser-based techniques, *etc.*) are needed for monitoring degradation of FR composites in the field.
- Further understanding of the relationship between polymer matrix properties and FR composite performance in practice may be useful, especially when qualifying new polymer formulations for use in infrastructure applications.
- Defect characterization has been conducted using IR thermography and is currently more of a qualitative measurement. More research is needed with this technique.

- Further guidelines on pull-off tests are needed such as the location and number of tests required as well as what to do if pull-off tests do not have the required strength or failure mode.
- Further laboratory tests of samples obtained from the field may be useful during inspections.
- The specific time frame in which long-term FRP composite inspection should take place is not generally provided in a guideline. Nor is there any guidance on inspecting FRP composites after a seismic event.
- Research with techniques such as Raman spectroscopy have only been used to assess the adhesive bond between epoxy and concrete, and future work with these techniques to assess how this adhesive bond changes after environmental exposure is needed.
- Overall, more work is needed to compare mechanisms of adhesion loss and failure in practice to available adhesion tests to provide better correlations for models.
- A better understanding of FRP composite debonding and strength loss (when applied to concrete) by freeze/thaw cycling and long-term cold weather exposure is needed to assess FRP assembly durability in cold climates. Furthermore, a comparison of freeze-thawed FRP assemblies in the laboratory to assemblies exposed outdoors is needed to validate the degradation pathways observed with accelerated conditioning.
- More studies are needed to develop reliable performance criteria for FRP assemblies prepared with deteriorated concrete.

5.2.2. Structural Level Research Needs

- Developing design standards and test methods for FRCM composites to enhance the applicability of this retrofit system in practice.
- Further research is needed to improve understanding of the effectiveness of FRP anchors. Moreover, future research should provide guidance on improving the effectiveness of FRP anchors in terms of fiber volume fraction of FRP anchors, anchor spacings, and geometric locations.
- The behaviors of FR composite retrofitted components under torsional loads needs to be better understood through experimental studies.
- Numerical modeling capabilities for assessing the response of components repaired with FR composites need further improvements.

- Numerical modeling capabilities for simulating the response of retrofitted structural components with FRP anchors needs further improvements.
- Further research is needed to improve understanding of the impact of environmental exposure on the long-term performance of full-size structural components.
- Research is needed to improve the calculation of strength reduction factors for the aggregated impact of multiple environmental factors.
- Improved measurement capabilities are required for *in-situ* long-term performance assessment of retrofitted structures.
- Numerical modeling of durability and aging of retrofitted structural components needs further improvement.

All research needs summarized in Section 5.2 were discussed to some extent at the workshop, except for the following: 1) the need for improved FRCM design standards, test methods, and uniformity in production, 2) the need for research that help improve the bond between fibers and cementitious matrices for FRCMs and 3) the need for long-term performance studies of FRP composites bonded to timber. The FRCM topics were likely not discussed since FRP composites are more widely used in the U.S. The use of FRP composites bonded to non-concrete substrates such as timber was discussed at the workshop (Section 3.1.1) but the durability of these assemblies was not discussed because the focus of the discussion centered on concrete substrates, the most common type of substrate used at the time the workshop was held. Nevertheless, these three research needs may require more attention going forward.

5.3. Key research needs from workshop concerning materials

The key research needs for materials that make up an FR composite structure, which include FR composites and the substrates to which they are retrofitted, were explored in the context of materials selection, initial performance of FR assemblies, material degradation during service life, and challenges in use of FR composites. In addition, practicing engineers require more guidance to improve their assessment of how an FR composite will contribute to the performance of a structure over its lifetime by improvement and development of inspector training programs, inspection test methods, durability and fire rating studies, and measurement science tools to understand the service life of FR composites in the field. The highest ranked research needs from the workshop concerning these issues are discussed in detail below.

5.3.1. Improvement of Inspector Training and Certification

The installation quality of FR composites is directly related to the workmanship on the job site. For this reason, it is imperative to provide thorough training to FR composite installers. A series of trainings are already available, but a certification program that spans multiple installation steps that include surface preparation, mixing procedures, and process control for installation schedules should be developed to better train FR composite installers. This is especially important since installation quality will impact the performance of the retrofit, improve the consistency of retrofit performance across the board, and prevent costly mistakes associated with re-installation of FR composites. Certification programs and more training courses can be developed by appropriate standard developing organizations.

5.3.2. Improvement of Inspection Test Methods to Reduce Uncertainty

The test methods used in the field to assess initial performance of FRP composite retrofits include the coin tap test for measuring the presence of voids between the FRP retrofit and the substrate, degree of cure, tensile testing of FRP witness panels prepared on the job site, and pull-off tests to measure both concrete substrate strength and adhesion of the FRP composite to concrete. The coin tap method is a fairly reliable but crude method to examine the installation quality of FRP composites. Improvement of this method or development of cost-effective, practical methods to supplement it may be worthwhile. Other new test methods to assess the initial performance of the FR composite retrofit should also be researched as the number and capabilities of current test methods are limited. Techniques to assess the saturation level of FRP fabrics in the field may also be useful as air and moisture entrapment can eventually lead to strength loss and FRP composite debonding from the substrate. New standardized test methods will help improve QA/QC during field inspection. Additionally, providing further detailed guidance on existing test procedures can remove some of the uncertainties involved in these test methods.

For the pull-off test and the tensile test, high variability in the results have been observed for various reasons, and further understanding or improvement of these test methods may be warranted. For tensile tests, issues with tensile test sample preparation and gripping procedures were identified as potential issues and more standardized guidance was recommended. For the pull-off tests, many discussions at the workshop indicated the practicality of the tests but described the ambiguity that test results could provide. Issues faced by users of the test in the field include the importance of the 200 psi pull-off test strength of the concrete substrate, the number and location of tests required, the use of this test method on curved substrates, proper use of the test for long-term inspections, and most problematically, interpretation of the pull-off test strength, failure mode data, and acceptable variability in the tests results. More systematic pull-off test studies may help to improve upon the test method. Furthermore, practical test methods that more directly assess the FRP composite bond to concrete may be worth investigating for use in the field.

5.3.3. Research on Application of FRP Composites to Non-concrete Substrates

The versatility of FRP composites beyond application to concrete substrates has been demonstrated by FRP composite retrofitting of both timber and steel. However, FRP composite application to these non-concrete substrates presents new challenges that require more materials research to support widespread use. Specifically, systematic research is needed to develop test methods relevant to the substrate (*e.g.*, pull-off test no longer relevant), provide information on the performance of this type of retrofit, and provide the bond strength requirements for non-concrete substrates in different applications and geometries. In the case of steel, an understanding of how different surface coatings and paints, varying surface roughness values, and the presence of existing corrosion can affect adhesion of FRP composite to the substrate are necessary.

5.3.4. Development of Metrology for Fire Rating

The effect of fire on FRP composites is likely to be detrimental since most of the polymers and adhesives used in these retrofits are flammable and degrade at temperatures experienced in fire. Further research on how to appropriately apply standardized test methods used for fire resistance of conventional building materials to fire resistance of FRP composites is needed. Since FRP composites degrade in a fire, it is important to determine how resistant FRP composites are to increasing fire loads. Guidelines must also be provided on the performance level the structural components will have to maintain when FRP composites are degraded in a fire.

5.3.5. Development of Inspection Protocols for FR Composite Retrofits at Later Stages of Service Life

Following long-term use of FR composites in the field, inspectors will need to have adequate protocols available to evaluate the change in performance of FR composites resulting from materials damage such as degradation or mechanical loadings, including after seismic events. Current inspection practices and the use of measurement techniques to assess the status of FR composites after long-term use are limited and do not adequately determine the degree of FR composite damage with respect to the time it has spent in its surrounding environment. Improving inspection protocols to include more information about materials damage will reduce uncertainty in the lifetime of FR composites and improve safety. In addition to pull-off tests and coin tap tests, test methods that detect the status of chemical and physical degradation of the FRP composite and the FRP composite-concrete interface need to be developed to enable timely repair or replacement of FRP composite retrofits with decreased loading capacity. This may require more research to determine chemical and physical indicators of degradation that can be detected and related to FR composite loading capacity.

5.3.6. Identification of Bond Degradation Mechanisms at the FRP Composite-Substrate Interface

One of the most common failure modes observed for FRP composite retrofits in the field involve debonding of the retrofit from the concrete substrate. Debonding of FRP composites can lead to a decrease in structural load capacity of the retrofit. Interfacial debonding of the FRP composite can occur in the presence of several environmental conditions such as freeze-thaw cycles, wet-dry cycles, salt intrusion, cold environments, degradation of the substrate, or a combination of conditions with or without added mechanical loading. If the FRP composites were initially attached under high humidity, low temperatures, or in the presence of moist concrete, this can also eventually lead to bond degradation. Systematic research of debonding mechanisms under controlled weathering and mechanical conditions would help improve understanding of FRP composite interface durability in the field and provide data to improve strength reduction factors and modeling capabilities.

5.3.7. Conduct Accelerated Conditioning Tests that are Representative of Outdoor Field Conditions and FR Composite Configurations

Accelerated conditioning tests that simulate long-term, outdoor field conditions for FR composites are needed to improve understanding of FR composite service life. Furthermore, outdoor weathering of the same types of FR composite samples needs to be conducted to compare to accelerated conditioning results. Since outdoor conditions are variable and there is always uncertainty in whether an accelerated conditioning protocol accurately simulates outdoor conditions, degradation observed in accelerated conditioning tests must be compared to degradation observed for the same FR assemblies exposed outdoors. Furthermore, accelerated conditioning studies and outdoor weathering studies need to be systematically designed with a consistent batch of FR assemblies and test methods. Unlike many current research studies where standalone FR composites are degraded, samples in future studies should contain the FR composite bonded to the underlying substrate in the relevant configuration to capture all possible indicators of degradation. During laboratory weathering, it is also important that FR assemblies be exposed to the same mechanical stresses they would experience in a given application. Measurement methods, including chemical and mechanical methods, must be developed to track degradation in both accelerated conditioning tests and outdoor tests. Once correlations are obtained between accelerated conditioning tests and long-term, outdoor exposures, improved service life prediction of FR composites can be achieved.

5.3.8. Effect of Scale on Tests

For practical reasons, laboratory tests to evaluate structural performance of FR composites are often conducted using smaller scale samples. This can include FR composite samples used in environmental durability studies and initial performance studies. FR composites are often applied over larger areas than represented by laboratory samples, and correlation between small-scale samples and true-scale samples are not always guaranteed. For this reason, more structural-scale laboratory test results should be compared to small scale laboratory test results with the similar test conditions and materials. In order to do this, smaller-scale testing reproducibility might first be necessary using round-robin testing.

5.4. Key Research Needs from Workshop Concerning Structures

A broad set of research and implementation activities need to be conducted to improve the state-of -practice and knowledge concerning the system level response of FR composite retrofitted structures. This effort includes improving the current design standards and inspection guidelines for FR composite retrofitted structures; experimental studies on retrofitted components and structures; improvement of inspection practices; and improvement of numerical modeling capabilities. Each of these key research needs is discussed in detail below.

5.4.1. Development of Design Standards and Guidelines

Although multiple design guidelines and standards exist for evaluation and design of FR composite retrofit systems for existing structures, current standards lack critical information required for design and implementation of FR composite retrofit systems. Specifically, there is a need in current standards for developing design and detailing requirements of FRP anchors. Moreover, with the increase in use of performance-based seismic design as the design philosophy, standards should include the required modeling parameters and acceptance criteria of structural components retrofitted with FR composites. Another issue related to development of standards is the existence of standards developed by different SDOs that may not align well. An open dialogue between these SDOs can improve the consistency between standards and also transfer knowledge between the organizations.

5.4.2. Experimental Studies

Experimental studies are needed to improve understanding of the performance of FR composite retrofitted components and structures, and to provide data required for development and validation of numerical models. Although multiple experimental studies have been conducted in the last three decades on the performance of FR composite retrofitted components, these studies were primarily focused on specific structural components (*e.g.*, columns) and were conducted up to a specific drift limit. There is still a great need to conduct experiments on different structural components and buildings retrofitted with FR composites that are not covered by existing experimental data. These tests need to be conducted at the component, subassembly, and system levels. FR composites are often applied over larger areas than represented by laboratory samples, and correlation between small-scale samples and true-scale samples are not always guaranteed. Thus, structural-scale experimental studies are needed to provide insight into the behavior of real structures. In addition, most of the current tests stop at 20 % loss of capacity. Future tests should capture the response of retrofitted components and structures all the way to the loss of capacity. Furthermore, FR composite durability studies should compare structural-scale laboratory test results to small-scale laboratory test results with similar test conditions and materials.

5.4.3. Improvement of Inspection Practices

Research is needed to improve existing inspection practices and develop new tools and techniques that can be adopted by inspectors. The existing inspection techniques may need to be modified to improve the reliability of the assessment of retrofitted structures over their lifetime; this includes providing guidance on the number and location of tests (*e.g.*, pull-off tests) as well as the time interval between inspections. Development and application of both destructive and non-destructive techniques and tools are also needed. Guidelines would also have to cover FR composite application in various geometries. The inspection methods have been more focused on the initial performance of buildings after FR retrofit installation, however, the applicability of methods such as the pull-off tests to assess the long-term and post-hazard performance of FR retrofit systems should be studied.

In addition to the need for improving the inspection measurement tools and techniques, inspection standards are needed to assess the status of FR composites right after installation, over the lifetime of the structure, and after a hazard event occurs. These standards can play an important role in achieving the desired performance of retrofitted structures.

5.4.4. Improvement of Numerical Modeling Capabilities

Numerical modeling capabilities need to be improved to enhance the accuracy of the initial performance assessment of retrofitted structures. Research is needed to improve the accuracy and capabilities of models from the materials level all the way to the structural level. Specifically, numerical modeling capabilities to simulate the response of retrofitted joints and connections as well as anchors require further development. Additional research is needed to provide input parameters required for advanced numerical modeling techniques, and to develop simplified modeling techniques that can be used by practicing engineers. The new and existing numerical modeling techniques need to be validated with respect to experimental or reconnaissance data to benchmark the capability of these models.

While current modeling capabilities are mainly developed to simulate the initial performance of FR composite retrofitted structures, there is a great need to extend the modeling capabilities to be able to capture the performance of a retrofitted structure over its service life. Environmental factors such as exposure of FR composite retrofits to humidity and temperature can impact the performance of a retrofitted structure over time. In addition, minor hazard events can impose minor damage to the building and FR composite retrofit that can accumulate over the building's service life. It is crucial to capture the impact of the damage due to the chronic or minor episodic events on the building, in order to accurately assess the performance of an FR composite retrofitted building and predict its service life and remaining capacity. In summary, research is needed to develop numerical models capable of simulating the impacts of degradation due to environmental factors as well as damage accumulation on the performance of FR composite retrofitted structures.

Appendix A: Research Needs from Chapters 3 (Materials) and 4 (Structures)

Materials:

1. Criteria for Materials Selections

# total votes	Research Need	Ranking
8	Development of criteria for FRP composite materials selection for non-concrete substrate (*e.g.,* steel, timber) applications	Highest
4	Evaluation & combination of performance specifications & test standards by neutral entities	Higher
4	Development of QA/QC metrologies for evaluation of materials selection	Higher
2	Identification of evaluation criteria of materials to determine interface quality between FR composites and a substrate	High
1	Assessment of the concrete substrate condition and evaluation of its effect on FR composite bonding properties	High

2. Initial Performance of FR Composite Materials

# total votes	Research Need	Ranking
16	Improvement of current test methods (QA/QC) to reduce uncertainty in the test results for determining initial performance	Highest
4	Identification of criteria for application of FRP composites to non-concrete substrates	Higher
3	Development of guidelines to address specific geometric issues during application	Higher
3	Development of metrology to measure the saturation level of resins	Higher
2	Input of parameters from initial installation for improved numerical modeling	High

3. Material Degradation During Service

# total votes	Research Need	Ranking
15	Establishment of correlations between laboratory accelerated conditioning test results and field exposure results	Highest
7	Establishment of inspection protocols and indicators of degradations	Highest
7	Identification of bond degradation mechanisms between FRP composites and substrates in various environments	Highest
3	Development of a database to document degradation mechanisms in field applications	Higher
2	Development of laboratory tests of FRP composites with through-thickness-reinforcements	High
1	Establishment of outdoor exposure sites and protocols for long-term durability studies	High

4. Challenges in Usage

# total votes	Research Need	Ranking
18	Development of guidelines and certifications for installations	Highest
7	Development of metrology for fire rating of FRP composites	Highest
7	Development of round robin tests and establishment of improved correlations between small-scale and structural-scale tests	Highest
5	Facilitating harmonization of specifications and test methods among various Standards Developing Organizations (SDOs)	Higher

Structures:

1. Initial Performance of Structures

# total votes	Research Need	Ranking
7	Testing at the Structural-scale	Highest
6	Improvement of Numerical Models	Higher
5	Testing of the initial bond of the FR composite	Higher
3	Improvement of the QA/QC of the installation process	Higher
2	Development of non-destructive techniques to provide a baseline for structural health monitoring	High
1	Improvement of the understanding of FR composite applications for different structural configurations	High
1	Development of better test protocols for characterizing *in-situ* performance	High

2. Long-term Performance of Structures

# total votes	Research Need	Ranking
20	Improvement of inspection practices	Highest
10	Development and validation of models that consider aging and accumulation of damage from minor events	Highest
4	Improvement of environmental reduction factors used in design	Higher
2	Validation of accelerated conditioning protocols using decommissioned field structures (forensic analysis)	High
1	Development of performance-based design for FR retrofits	High

3. Design Consideration and Standards

# total votes	Research Need	Ranking
35	Development of Design standards and Guidelines	Highest
13	Experimental research on FR composite retrofitted structural components and buildings	Highest
4	Improvement of numerical models for design	Higher
4	Development of backbone curves using experimental data	Higher
2	Database of experimental results	High
1	Implementation and adoption of new standards and methods	High
1	Development of lifecycle modeling and decision-making tools	High
1	Development of reliability-based design factors	High

Appendix B: May 15, 2018 FRP Workshop Agenda

May 15, 2018 (Tuesday), NIST, Gaithersburg, MD

Conference Room: Lecture Room B - Building 101

Time	Title	Speaker	Location
8:00 – 8:30a	Registration		Lec B
8:30 – 8:35a	Welcoming Remarks	Steven McCabe	Lec B
8:35 – 8:50a	Workshop Opening Remarks	Jason Averill	Lec B
8:50 – 9:00a	Workshop Framing	Steven McCabe	Lec B
9:00 – 9:20a	Use of CFRP for Correcting Deficiencies in RC Structures	James Jirsa	Lec B
9:20 – 9:40a	FRP Research and Guideline Needs for the Practicing Engineer	Bret Lizundia	Lec B
9:40 – 10:00a	Establishing the Critical Requirements or FRP Materials used as Externally Bonded Reinforcement for Strengthening Structures	William Gold	Lec B
10:00 – 10:20a	Challenges and Research Needs on Testing of Externally Bonded FRP Systems	Charles Bakis	Lec B
10:20 – 10:45a	Panel Discussion	John Myers	Lec B
10:45 – 11:00a	Break		Lec B
11:00a – 12:30p	Breakout Session I		Lec B, B111, B113
12:30 – 1:30p	Lunch		Cafeteria
1:30 – 3:00p	Breakout Session II		Lec B, B111, B113
3:00 – 3:30p	Break		Lec B
3:30 – 4:00p	Report-out from Breakout Sessions		Lec B
4:00 – 4:30p	Large Group Discussion	John Myers	Lec B
4:30 – 4:40p	Closing Remarks	Lipiin Sung	Lec B
5:00p	Happy Hour		Hilton

Appendix C: Workshop Attendee List

Last Name	First Name	Organization	Attendee Type
Alkhrdaji	Tarek	Structural Technologies	Industry
Arnold	Scott	Fyfe Co. LLC	Industry
Bakis	Charles	Pennsylvania State University	Academic
Brena	Sergio	University of Massachusetts Amherst	Academic
Dukes	Jazalyn	EL/NIST	Federal Government
Erdem	Ibrahim	Exponent	Consultant
Fathali	Saeed	Simpson Strong-Tie	Industry
Ferraris	Chiara (Clarissa)	EL/NIST	Federal Government
Gilman	Jeffrey	MML/NIST	Federal Government
Gold	William	BASF Corporation	Industry
Goodwin	David	EL/NIST	Federal Government
Jirsa	James	Univ. of Texas, Austin	Academic (Via Webinar)
Hota	Gangarao	West Virginia University	Academic
Kanitkar	Ravindra	KL Structures Group, LLP	Industry
Kim	In Sung	Degenkolb Engineers	Consultant
Kim	Yail	Univ.of Colorado Denver	Academic
Kim	Jae-Hyum	EL/NIST	Federal Government
Lew	Hai S.	EL/NIST	Federal Government
Lizundia	Bret	Rutherford + Chekene	Consultant
Lopez de Murphy	Maria del Mar	Modjeski and Masters, Inc.	Consultant
Myers	John	Missouri University of Science & Technology	Academic
Nolan	Steven	Florida Department of Transportation	State/Local Government
Orton	Sarah	University of Missouri	Academic
Rosenboom	Owen	Wiss, Janney, Elstner Associates, Inc.	Consultant
Streim	Justin	Simpson Strong-Tie	Industry
Sung	Li-Piin	EL/NIST	Federal Government
Tatar	Jovan	University of Delaware	Academic
Thostenson	Erik	University of Delaware	Academic
Zatar	Wael	Marshall University	Academic
Zhang	Chun	Georgia Institute of Technology	Academic

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