Research Needs for Fiber Reinforced (FR) Composite Retrofit Systems in Buildings and Infrastructure

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Synopsis: Fiber Reinforced (FR) composites have become increasingly popular as retrofit solutions for buildings and infrastructure due to their ease of application, lightweight properties, and corrosion resistance. However, there are still research needs in this area that hinder wider adoption of fiber reinforced polymers (FRP) retrofit solutions and limit the understanding of initial and long-term performance of FRP-retrofitted components and structures. This paper presents the findings of an extensive literature review conducted by the authors to identify the state-of-the-art of FR composites, FRP-retrofitted structures and infrastructure, and guidelines and standards that address the testing, evaluation, and design of these systems. Research needs for FRP composites identified during a National Institute of Standards and Technology (NIST) workshop that convened a group of experts in industry, academia, and manufacturing are discussed. An overview of those research needs that received the highest ranking in this workshop are presented in this paper. Implementation of these ranked research needs by the FR composite research community, including NIST, will serve to impact and advance the field of FRP retrofit of buildings and infrastructure.

Keywords: durability; earthquake engineering; fiber reinforced polymers (FRP); infrastructure; resilience; retrofit

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INTRODUCTION

Fiber reinforced (FR) composites (including fiber reinforced polymer, FRP) and fiber reinforced fabric cementitious matrix (FRCM) composites are high-strength materials that have been used in civil engineering applications for more than 20 years. FR composites offer some advantages over traditional construction materials such as concrete and steel, that include high capacity to resist loads, ease of application, lightweight properties, and corrosion resistance. There are many types of FR composites systems, including externally bonded (EB) FRP, near surface mounted (NSM), internal rebar reinforcement, concrete filled FRP tubes, pre-cured FRP laminates and jackets, and pultruded bridge decks and girders. FRP materials applied to infrastructure typically consist of glass, carbon, aramid, or basalt fiber, while the most common type of polymer matrix used is epoxy.

This paper presents research needs identified in a workshop conducted by the National Institute of Standards and Technology (NIST) primarily for EBFRP composites attached to a concrete substrate, as this is the most common use of FR composites for retrofit of buildings and infrastructure. However, it is acknowledged that EBFRP applied to other substrates, FRCM, and internal FRP reinforcement are becoming more widespread, and specific research needs of these applications are worthy of investigation.

The resilience of our built environment to ageing and extreme events can be improved with the use of EBFRP composites. EBFR composites can be applied to repair, strengthen, or retrofit structural components against extreme events, increase capacity under gravity loads, or reduce further deterioration of underlying reinforcement. Use of EBFRP is particularly useful in efforts to extend the life of the nation’s aging infrastructure, as these composites offer rapid installation and the ability to increase a structure’s lifetime until full replacement with a new structure can be completed. EBFRP composites are being widely used on highway structures across the country, as has been reported by the National Cooperative Highway Research Program (NCHRP) of the U.S. Department of Transportation [1].

NIST recently conducted an extensive literature review to determine the state of the art for use of FR composite systems in retrofit of buildings and to identify relevant research gaps. The literature review was mainly focused on characterization methods to assess the performance of EBFRP at three scales : material, assembly, and structural. A workshop with participation of key stakeholder was conducted by NIST in May of 2018 to compliment the findings of the literature review and confirm identified research needs in a comprehensive report with recommendations for researchers and practitioners. An overview of the highest-ranking research needs in the workshop are discussed in this paper, with the NIST Special Publication 1244 providing details on the literature review, workshop, and key research needs at the material and structural levels [2].

RESEARCH SIGNIFICANCE

While the use of FRP composites for retrofit of buildings and infrastructure becomes more prevalent across the United States, there are still major questions surrounding the initial and long-term performance of FRP both as individual materials and in retrofitted structures. This paper brings attention to the NIST Special Publication 1244 [2], which provides an extensive literature review on externally-bonded FR composite systems, and key research needs identified by experts and experienced practitioners who participated in the NIST workshop.

STATE OF THE ART OF FR COMPOSITE RETROFIT SYSTEMS ASSESSMENT

One of the goals of NIST Special Publication 1244 ("the report") [2] was to identify the state-of-the-art of FR-retrofitted buildings and infrastructure. The report outlines types of FR composite applications, benefits for structural repair and retrofit, and an overview of intended lifetime of FR composite repairs and retrofits. The report also focused on the current materials characterization methods and techniques for retrofitted structures to determine the state-of-practice of assessing the initial and long-term performance of FR composite systems and research needs in that area. This section discusses the materials characterization and performance at the three scales illustrated on Fig. 1: 1) standalone FRP composites, 2) FRP composite assemblies (i.e., composites attached to a substrate), and 3) FRP-retrofitted structures. These scales were investigated individually to identify material-level research needs and solutions that can be scaled to the system and component levels and improve structural performance. At each scale, material and structural characterization methods are organized by initial and long-term performance. For the FRP composites and EBFRP assemblies, destructive and non-destructive testing methods in the field and laboratory are described. While for the EBFRP-retrofitted structures, experimental and numerical studies are discussed.

Materials Characterization Methods to Assess FRP Composite Performance

Testing methods that determine the FRP initial and long-term properties are of interest in evaluating the performance of composites at the material level using standalone FRP composites. The initial properties of FRP composites are typically assessed by testing the FRP composite alone, and not the assembly. There are several ASTM standards that determine mechanical properties of FRP composites, such as ASTM D7565 for tensile tests [3,4], ASTM D7264 for flexural tests [5], ASTM D2344 or ASTM D5379 for interlaminar shear testing [6-8], and ASTM D2990 for creep loading [9]. ASTM standards also exist to determine other important characteristics of FRP composites, such as ASTM D3171 for void detection in the matrix [10,11], ASTM E1640, ASTM E831, and ASTM E1356 for glass transition temperature [10,12-15], and ASTM D6969 and ASTM E831 for coefficient of thermal expansion [14, 16]. Several of the testing methods mentioned here could be modified and improved with the required consensus by stakeholders and users. For example, further understanding of the relationship between the polymer matrix properties and the FRP composite performance in practice would be useful and research is needed to address this topic.

The chemical properties of FRP composites can be measured prior to use, but often this is not done in practice as FRP composite durability is not broadly tracked in the field. Attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) can measure chemical properties of the polymer matrix [17], while Raman spectroscopy may be used to assess information about the polymer matrix and fiber composition [18,19]. Thermal properties like glass transition temperature and creep/fatigue behavior can be assessed with several types of techniques [12]. Imaging techniques, such as scanning electron microscopy (SEM) can be used for cross section analysis of composites to determine microcracking and voids in the composite [20, 17]. The use of these techniques to determine chemical and microstructural properties of FRP composites would be useful to evaluate on smaller samples collected from the field during initial FRP installation to have the ability to track long-term changes to material properties in the field without invasive mechanical testing. However, use of these techniques is limited due to costs and lack of standards and procedures that can be used in practice.

Testing of FRP composites under various environmental processes is important to determine the long-term performance of these materials in the field, as illustrated in Fig. 2. FRP composites can be exposed to environmental effects, such as UV radiation, moisture, arid conditions, salt water, high temperatures, and freeze/thaw cycles. Dalfre etal. [76] examined the effects of weathering under dry winter and hot/humid conditions on the epoxy resin degradation and the performance of a strengthened beam compared to a reference specimen. The study revealed after 8 months, the epoxy resin had a significant reduction in tensile strength, and a lesser effect on modulus of elasticity. However, properties of the FRP composite remained similar. Acceptance criteria International Code Council Evaluation Service (ICC-ES) AC125 provide recommended environmental conditions to be tested to determine the changes in tensile and chemical properties [10]. FRP materials must exhibit 90 % retention of tensile properties after 1000 hours of exposure, and 85 % retention after 3000 hours. The FRP composites are also visually inspected for cracks, chalking, and fiber-matrix debonding with a microscope.

Several imaging techniques have been used to detect FRP composite property changes. Digital image correlation (DIC) can monitor mechanical property changes before and after environmental exposure, typically using tensile, flexural and creep deformation testing data [21, 22]. SEM and Raman spectroscopy can detect fiber degradation by monitoring fiber bands that appear at the surface of composites [23, 18, 19]. Mass loss or cross-sectional imaging for thickness loss can detect polymer removal from the composite during degradation [17]. While some of these techniques may currently be more commonplace in a laboratory setting, advances in handheld instruments may make them useful also for in-situ testing of FRP composites. Currently, non-destructive field tests (NDT) include acoustic emission [63], thermography [64], laser reflection, and laser-based acoustic tests [65]. These tests can detect internal changes in FRP composite material, such as cracks and voids, before and after environmental exposure.

Materials Characterization Methods to Assess FRP Assembly Performance

As with the characterization of standalone FRP composites or materials, literature review on performance of FRP composites attached to a substrate - otherwise known as FRP assembly performance - focused on characterization methods to assess the initial performance and long-term performance. The literature review revealed two types of tests methods: laboratory measurements to pre-qualify the system, and in-situ tests used during installation and monitoring of performance over time to ensure quality-control. The parameters tested are the material properties of the FRP composite, the bond between the FRP composite and the substrate, and the condition of the substrate.

Quality-assurance and quality-control (QA/QC) procedures must be followed during the installation process [12]. Documentation of installation conditions, such as weather and substrate, and fiber fabric and adhesive properties [12, 24] should be made. FRP witness panels are created on-site during FRP composite installation and sent to a laboratory for tensile testing and sometimes degree of cure measurements using ASTM D3418 [12, 24, 25]. Pull-off tests to determine the bond quality of FRP to concrete are performed and recorded, as well as locations of delamination and air voids. More research is needed to determine how the initial conditions of the concrete during FRP installation affect the long-term performance of the FRP bond to the concrete substrate. If inspection procedures and initial conditions are well documented, this will help assessment measures of long-term performance.

Other non-destructive methods available to detect voids, include acoustic sounding, acoustic laser techniques, ultrasonic inspection techniques, and infrared thermography. Acoustic sounding techniques, usually performed with a coin or a small hammer, offer simple ways to detect defective regions by tapping on the surface and listening for hollow sounds that indicate potential voids. Acoustic laser techniques initiate vibrations within the FRP assembly and characterize the resulting vibrational behavior using a laser beam to detect hidden defects. Ultrasonic inspection techniques impart an ultra-wide band wave of the FRP assembly and measure the reflected waves off the FRP assembly surface and bondline to detect voids and determine characteristic responses of different materials (i,e., FRP composites and concrete) [65]. Infrared thermography can analyze the intensity of infrared radiation dissipated from the FRP composite surface after heating to detect hot spots that indicate the possible presence of voids between the FRP composite and the substrate [64].

One of the most common destructive field inspection techniques are pull-off tests to evaluate the adhesion status of the FRP composite to the substrate. ASTM D7522 [26, 27] details the test, which involves drilling through the FRP assemblies into the substrate, applying a metal disk to the FRP assembly surface using high strength adhesive, and pulling off the disk at a controlled rate until failure. Guidance documents [12] indicate that the failure or break should occur within the concrete layer, and the pull-off strength should reach at least 1.4 MPa (200 psi). In practice, there have been reports of high variability in terms of pull-off test strength and mixture of failure modes, with many potential sources of variability identified but not necessarily quantified, including substrate conditions, coring conditions, types of FRP adhesives, and surface preparation. There is no guidance available for recourse in the event of adhesive failures or tests that don’t meet the bond strength requirement. The pull-off test is also highly localized and may not represent the bonding conditions of an entire EBFRP-retrofitted surface. Further research and guidance are needed on this subject.

Understanding the long-term performance of the assembled FRP composite and substrate is essential in determining if the retrofit is performing or will perform as expected in case of an extreme event. Guidelines, such as ACI 440 [12], state that owners of retrofitted structures should periodically assess the performance of FRP composite systems with a visual inspection, NDT, and destructive testing. However, the timeframe for these inspections are not given, and there is no guidance on inspecting FRP composite systems after a seismic event. Some state DOTs do provide guidance on inspection timelines for bridges. For example, the New York State Department of Transportation (NYSDOT) states that FRP composite systems should be inspected 3-4 months after installation and every two years after that [28]. There is more guidance needed on this topic for all types of structures.

The non-destructive and destructive techniques used to determine the initial condition of FRP composite systems are the same ones recommended for inspection and assessment of these systems in the field over time. For laboratory tests, ACI 440.9R[29] recommends FRP assembly specifications and dimensions for evaluation of long-term FRP assembly performance following weathering. Specifically, FRP composites are bonded to a concrete prism to study the mechanical properties before and after accelerated conditioning or outdoor exposure [29]. Three-point bending tests, as specified in ASTM D7958/D7958M [30], are typically performed. Additional tests may be performed on these specimens to identify degradation mechanisms. For example. chemical changes in the fiber and polymer matrix can be assessed using Micro-Fourier Transform Infrared Spectroscopy, Raman spectroscopy mapping, and imaging techniques (optical or electron microscopy). For example, Reay and Pantelides [70] used thermography imaging to assess the condition of external FRP on a bridge after 3 years. Future work is needed to assess the chemical and physical bond between FRP composites and concrete and how the adhesive bond changes after environmental exposure [31,32].

Assessing the Performance of FRP Retrofitted Structures

The state of research in the initial and long-term performance of FRP retrofitted structures is discussed in this section. Initial performance refers to the performance of the structure immediately after retrofit, while long-term performance refers to the performance after long-term use on a structure, outdoor weathering, deterioration, or an acute event. Initial and long-term performance are further divided into three subtopics: experimental studies, *in-situ* studies, and numerical studies. Experimental studies on EBFRP composites have shown the performance enhancements that can be derived from the application of FR composites on structural components [33-35,71]. Performance enhancements include improved confinement, load-bearing capacity, blast resistance and shear resistance, all of which depend on the application and design intent of the retrofit. EBFRP composite application to different components, such as columns, walls, beams, and beam-column joints will vary due to the different performance enhancements sought for each component. Fig. 3 illustrates several components and types of FRP applications. For example, confinement is a top priority for columns, especially columns that are damaged or need to be upgraded. RC beam-column joints may suffer from nonductile detailing that can lead to shear failure of joints. These performance concerns can be addressed with EBFRP composites and require different techniques for the design and application. Experimental studies on retrofitted columns [36-38], beam-column joints [39-44,72], walls [45-47], and slab-column connections [66] illustrate the work that has been conducted to assess the initial performance of FRP-retrofitted structures.

Repair of structural components with EBFRP composites is also a common use of the material. A major benefit of FRP is its effectiveness as a rapid repair system for damaged components after a natural hazard event. When used in combination with materials such as early-set concrete and quick-set mortar, RC components such as concrete piers and columns have been demonstrated to regain strength or change to a ductile failure mode when repaired with FR composites [48, 49]. The EBFRP repair technique is particularly useful for impact-damaged components such as prestressed beams on overhead passes on highways. Researchers have demonstrated the usefulness of this techniques through experimental testing as well [49-52,73]. Vukovic etal [69] performed structural-scale testing on aged concrete T-beams retrofitted with external FRP. After 10 years of outdoor weathering, concrete beams were retrofitted with CFRP strips on the flange and tested with different loading protocols. The results showed the simple strengthening technique used was effective in retrofitting the beams, increasing flexural strength, and reducing deflections.

Fiber anchors in combination with application of FRP wraps and laminates have recently received more attention in the research community, as it has become clear that anchors are necessary for delivering the desired performance of an FR composite retrofit. FRP anchors improve the effectiveness of the retrofit by delaying or preventing premature debonding of the FRP wrap from the component [53]. Several components have been tested in the laboratory with anchors to assess the effects of placement, size, and anchor type on the performance. Smith et al [53] found that including FRP anchors in the EBFRP retrofit design of an RC slab increased the strength and deflection by 30 % and 110 % respectively relative to an EBFRP retrofit without anchors. Koutas and Pityzogia [54] find that the placement of FRP anchors matters in the case of retrofitting an RC T-beam, as anchors placed inside the flange of a T-beam outperform those placed on the web of the T-beam. Other researchers found compelling results for testing bridge girders and walls [55,56,74,75]. However, there was a consensus in the literature that further research is necessary to identify the optimal placement and fiber content of anchors in this context and with various other building components. While Grelle and Sneed [67] concluded in 2013 that there was an insufficient amount of available test data to develop standards for anchorage, a 2020 state-of-the-art review of experimental studies on FRP anchorage in strengthened RC beams [68] found that while many studies have been conducted lately, there still remains a research need to further investigate the effects of the anchor technique and various parameters on the performance of the structure.

Numerical studies are a necessary complement to experimental studies to improve understanding of the performance of FRP-retrofitted structures. Experimental studies provide data that is used to calibrate numerical models for more accurate representation of structural performance. Many more numerical models and analyses can be run than experimental tests, thus developing effective numerical modeling techniques for FRP-retrofitted structures is important. Researchers have developed models for various structural components, repaired structures, the bond behavior between the FRP composite and the substrate, as well as the behavior of FRP retrofitted structures with FRP anchors. When modeling repaired structures, the two-phase and damage index method appear in several papers [34, 57, 58]. This method requires repair elements to be incorporated into the model at the beginning, which are used to replace damaged portions in the second phase of analysis. While research to date has found good agreement with this method, research on the topic of repaired components remains limited. The same is true with numerical simulation studies of FRP-retrofitted structures with FRP anchors [59], so there is a need for further research on this topic.

Environmental exposure of FRP composites bonded to the exterior of structures is a major cause of material and bond degradation. The effect of environmental conditions, such as UV radiation, alkaline environments, salt water, and freeze-thaw cycles, have been the subject of research studies mentioned earlier in this paper. There is still a challenge of correlating the effect of environmental exposure to long-term structural performance of FRP-retrofitted structures since most tests conducted involve simulated accelerated laboratory conditioning without validation by outdoor weathering tests. The literature review revealed that there are limited studies available on this topic, and there is a need for more research on validation of laboratory tests and evaluation of performance of FRP-retrofitted structures subjected to outdoor weathering. To address this, environmental reduction factors in the design process can be applied to account for expected deterioration of the strength of FRP composites, such as those used in ACI 440.2R-17 [12]. These reduction factors have only few references listed for accelerated conditioning tests, without outdoor weathering validation or an indication of their exact origin. Dolan et al. [60] developed test procedures to provide data to compute strength reduction factors for only two types of environmental conditions. There is a need for more research on producing environmental strength reduction factors based on experimental testing that would cover a range of possible field conditions.

Field studies and observations offer an opportunity to fill in the gaps from the limited available experimental tests for long-term performance of FRP-retrofitted structures. Since many FRP composites have been in use in civil construction for over 20 years, there are ample opportunities to study FRP composites in-service to understand the long-term performance of FRP retrofitted structures. National departments of transportation (DOTs) are a potential source of valuable information, as they have used FRP composites for bridge and infrastructure repairs. Hamilton et al. [61] studied a retired bridge girder after 10 years of exposure following repair and observed that chloride intrusion was lower in areas covered with FRP composites as compared to areas without FRP, indicating that FRP composites may provide some protection to the internal steel reinforcement from corrosion. Simpson et al. [62] monitored cracks of a repaired bridge for four years after retrofit and did not observe any further crack movement. The literature review revealed that in-situ research on the long-term response of FRP-retrofitted structures is sparse and needs more attention, as is the case for numerical modeling and simulation of FRP structures accounting for durability issues and aging effects.

NATIONAL WORKSHOP FOR RESEACH NEEDS ON THE PERFORMANCE OF FR COMPOSITES SYSTEMS

On May 15, 2018, NIST convened a stakeholder workshop that focused on research needs on the performance of FR composites systems. The goal was to receive input from a broad range of stakeholders through facilitated discussions around the topics of material and structural level research needs. The invited participants included representatives from other federal agencies, academia, private engineering firms, standards and professional organizations. Leaders in this field provided keynote speeches, addressing the major research needs from their perspective. The participants were asked to join one of three concurrent breakout sessions, during which an open discussion was facilitated about the research needs concerning two aspects of FR composite performance: material performance of FR composites and structural performance of FR composite retrofitted structures. The research needs and concerns discussed during the sessions were written out for the discussion group. After the discussion, participants were given six “voting” stickers, which they could use to choose the most important issues from their perspective. Participants could use up to two stickers on a particular issue to indicate weighted importance. Fig 4. shows examples of the voting method used by participants in the breakout sessions during the workshop. After all votes were placed, NIST staff noted all research needs having at least one vote and ranked them according to the number of votes to determine the highest priorities. Research issues for each topic were ranked based on the number of votes received and given a priority ranking: High (1-6 votes), Higher (7-10 votes), and Highest (10+ votes). In this section, we will discuss the issues that received a ranking of Highest priority by the participants. More information on the workshop and research needs discussed during the workshop is provided in NIST Special Publication 1244 [2].

Research Gaps in Material Performance of FR Composites

The research gaps were divided into four subtopics during the workshop: (i) materials selection; (ii) initial and (iii) long-term performance of FR assemblies; and (iv) challenges to usage. These subtopics were determined prior to the workshop based on the earlier literature review. Since reliable information on the materials characteristics are necessary to accurately determine the performance of a retrofitted component or structure, the research gaps are of particular importance to designers who would like to use the FR technology. The focus of each subtopic is outlined in the following paragraphs:

(i) Materials selection refers to the available specifications and codes and standards that can be used to facilitate selection of materials for a construction project. This subtopic had one research need that ranked as Highest: development of criteria for FR composite materials selection for non-concrete substrate application. The literature review indicated that most FR composites applied in the field involve a concrete substrate. However, there was interest amongst the workshop participants for more attention to the development of criteria for use of FR composites on non-concrete substrate materials, such as timber and steel. The application of FR composites to timber components has been demonstrated but there are only few studies on the effectiveness or performance improvement of the retrofit. There is also interest in applying FR composites to steel structures, but quality control measures have been difficult to implement due to variations in the surface conditions of steel. Participants felt that there are potential benefits for these types of applications; however further research is needed to understand the performance, bond quality, inspection methods, and materials selection criteria for non-concrete applications.

(ii) Initial performance of FR composite materials refers to the timeframe of installation in interior and exterior applications. Proper installation is essential to ensure the intended performance of FR assemblies. Improving the installation process and the inspection protocols after installation is a high research priority. There was one issue that rose to the ranking of Highest for this subtopic: improvement of current testing methods (QA/QC) to reduce uncertainty in test results for determining the initial performance. Testing methods that provide consistent, understandable results are critical for consistent evaluation of FR composites after installation. The most commonly used pull-off inspection method, tests the bond strength of an EBFRP composite to the concrete substrate. Pull-off test results have often been reported as highly variable with large uncertainties. Thus, the pull-off test requires improved understanding of factors that contribute to variability and more guidance on how to interpret variable results. Research to address the level of uncertainty in the pull-off test, or development of alternative tests to determine the FRP composite bond strength, is needed. Similarly with FRP witness panels which are created on site during installation, research efforts to improve material testing methods (e.g., tensile tests) and protocols to reduce the variability in test results are needed.

(iii) Long-term performance of FR composite materials refers to material degradation that can lead to performance changes during the service life of the retrofit. FR composite materials, particularly those used in exterior applications, are exposed to various environmental conditions such as ultraviolet (UV) radiation from the sun, freeze thaw conditions, alkaline and acidic conditions, and saltwater. The durability of FR assemblies can be affected by the fiber, matrix, and bond degradation between the FR composite and substrate materials. This subtopic generated three research needs with a ranking of Highest during the workshop.

   a. The first need is the establishment of correlations between laboratory accelerated conditioning test results and field exposure results. Outdoor weathering experiments are a challenge to conduct because outdoor weathering can take much longer than laboratory weathering or conditioning, thus making accelerated laboratory testing a preferred method of determining the durability of FR assemblies. However, accelerated laboratory weathering results may not always be relevant to outdoor weathering results because of the unpredictable nature of outdoor conditions. It is important to correlate accelerated conditions to outdoor conditions to ensure the same degradation modes are properly simulated in accelerated laboratory weathering tests. Otherwise, unexpected FR assembly failures may occur in the field or failures observed in accelerated laboratory tests may not actually occur outdoors. Furthermore, it is important to validate the acceleration factors of laboratory weathering tests by comparing to long-term outdoor weathering tests. Changes in accelerated weathering test designs may be warranted to improve simulation of degradation that actually occurs in the field. Furthermore, environmental degradation tests will likely need to incorporate fatigue and creep stresses.

b. Establishment of inspection protocols and indicators of degradation was also ranked Highest. Inspection of FR composite retrofits over the lifetime of a structure is important to ensure the retrofit will perform as expected. Current inspection methods do not capture the degradation rate of the FRP composite or the underlying substrate. For example, pull-off tests are used over time to test the bond strength, but there is no guidance on acceptable pass/fail criteria as part of an inspection. Furthermore, acoustic sounding is used to identify areas of debonding, but is not accurate for determining size and shape of debonded areas. Alternative techniques to assess bond strength and debonding are needed, and they should be practical, cost-effective, and representative of the entire FR assembly surface (e.g., in contrast to being localized like the pull-off test). There is also no guidance on when removal of FRP is necessary if the underlying substrate is degraded and in need of repair. Therefore, there is a need for establishing inspection protocols that clearly provide guidance on when FR composites need to be removed and/or replaced.

c. Identification of bond degradation mechanisms between FRP composites and substrates in various environments was the final research need that was ranked Highest under this subtopic. Similar to the other sub-topics, the need to identify methods that 1) determine specific bond degradation mechanisms between FRP and underlying substrate and 2) evaluate how different environmental factors, including in combination, contribute to bond degradation was highlighted. This is important because the bond between the FRP composite and underlying substrate has been identified as the weakest link to the FR assembly, and the point at which failure is most likely to occur due to material degradation. The effects of initial curing conditions, underlying substrate condition such as concrete moisture content, and other factors all can have a detrimental effect on the bond, and research is needed to improve understanding of the degradation mechanisms and develop testing methods to assess the bond degradation. Ultimately, the goal is to accurately determine the service life or remaining service life of an FR assembly.

(iv) Challenges in usage refers to impedances to a more widespread use of FRP in civil infrastructure, even after 20 years of use in the field. These challenges include improvements to FR installation procedures, metrology for proper installation and inspection, and coordination related to the FRP installation. Three research needs rose to the rank of Highest for this subtopic:

a. Development of guidelines and certifications to ensure proper installation and achieve desired structural performance and service lifetime. There is a need for widespread certification programs for the multiple installation steps required during FR composite retrofit, including surface preparation, epoxy mixing, and process control for installation schedules. Standards developing organizations (SDOs) can contribute to the development of these training programs so that they are made widely accessible. In addition to installation training, inspection procedures on how to evaluate installation quality is important, as for example, in detecting debonded regions after installation which may be difficult due to being covered by FRP.

b. Metrology for fire rating of FRP composites. It is common knowledge that mechanical properties of FRP materials change with increased temperatures. With glass transition temperature of FRP materials lower than the temperatures that may be experienced in a fire, deterioration of composite performance will occur in the event of a fire. Currently, the standardized testing methods have been developed for more traditional materials, such as timber, concrete and steel. There is a need for guidance on assessing the failure criteria of FRP composites and the impacts to structural performance during a fire event.

c. Development of round robin tests and establishment of improved correlations between small-scale laboratory and large structural-scale (or full-scale) tests. Small-scale testing is often used to determine the structural performance of FRP composite components due to reduced costs and time compared to structural-scale testing. However, the variations of data amongst these types of tests present a challenge when attempts are made to compare different tests and reproduce the results. Validation of small-scale tests with structural-scale tests will improve correlation of accessible small-scale tests to real-world structural-scale tests. In parallel, the dataset of available structural-scale testing results can be increased.

Research Gaps in Structural Performance of FR Composite Retrofitted Structures
The topic of research gaps was broken down into three subtopics determined prior to the workshop based on the literature review: (i) initial and (ii) long-term performance of structures, and (iii) design consideration and standards, all discussed in detail below:

(i) Initial performance of structures refers to structural condition at the time of retrofit, including consideration of the age and condition of the underlying structure. This subtopic discusses the needs for experimental studies, challenges in numerical modeling, and capabilities to overcome those challenges. The highest research need emerged from this subtopic was large scale structural testing. The workshop discussion and literature review suggest that there is still much to learn from testing FR retrofitted structures at the structural or large scales. While there have been tests in the past on components such as structural columns and beams, there are other components that have limited test data available, such as diaphragms, shear walls, and large structural assemblies. Testing at the structural scale can identify phenomena not observed at small or material-level scales, and enhance our understanding on the effects of dynamic loading on performance. Information from large-scale testing can be used to advance numerical models, as well as design and testing standards.

(ii) Long-term performance of structures refers to understanding the performance of retrofitted structures over time. There are concerns that FR composites may age in a way that can adversely impact long-term performance. Specifically, environmental factors can lead to degradation in the composite material and bond, affecting structural performance, as is the possibility of changing or increasing external loads over time and having acute loads from earthquakes that lead to substrate cracking, FRP debonding, and fiber rupture. Thus, the discussion around this subtopic focused on experimental and numerical research needs to assess structural performance and modeling over time that accounts for aging, degradation, and acute external loads. The two research needs that had a Highest ranking in the workshop are:

a. Improvement of inspection practices. This need can be further broken down into two categories: guidelines for inspectors, and measurement science tools for in-situ field testing. There is a need for improved and standardized guidelines to assess performance changes of retrofitted structures over time. Guidance such as visual inspection techniques, timing of inspections, and what measurements to employ are needed. Further guidance on post-event inspection after earthquakes and other hazards should also be developed. In addition to guidelines, there is a need for measurement science tools for in-situ, nondestructive testing of retrofitted structures. Non-destructive evaluation (NDE) techniques are important to identify as FR composite systems can hide the substrate transformations that occur over time. Techniques such as infrared thermography and ultrasonic pulse techniques need more experience in the field and lab to determine their usefulness. Pull-off testing to evaluate changes in bond strength needs further guidance on where to perform said tests. Initial environmental conditions and in-situ testing results should also be recorded and logged during FR retrofit installation to form a baseline that allows for better understanding of long-term changes to the FR retrofitted structure.

b. Development and validation of models that consider aging and accumulation of damage from minor events. These models can help predict the service life of FR retrofitted structures and help prevent structural failures. Damage accumulation can be incorporated into these models to determine the performance of structures in the event of acute hazard events such as earthquakes. Validated models can also inform the design of FR composite retrofitted structures. Models that are currently in use for initial performance can be updated with cumulative damage in order to capture the long-term performance. Improved modeling capabilities that include performance improvement from anchorage and bond performance loss are needed, as those capabilities are not currently available. After these models are developed, validation with field data on environmental degradation, aging, and acute event performance is needed. Validated numerical models can then be used to develop performance reduction factors for use in design.

(iii) Design considerations and standards refer to research and implementation activities that result in design and evaluation criteria, guidelines and standards for FR composite retrofit systems, and evaluation of existing retrofitted structures over time. Developing standards is challenging due to the needs for fundamental research on the initial and long-term performance of systems. Current Performance-based Seismic Design (PBSD) standards do not have specific information for the design of FR composite retrofitted systems, and guidelines by other standards developing organizations (SDOs) do not necessarily align. Two research needs rose to the ranking of Highest priority for this subtopic:

a. Development of design standards and guidelines, and experimental research on FR retrofitted structural components and buildings. There is a need for guidelines on detailing requirements for FR composite components. For example, even though it is commonly acknowledged that anchoring of FR composite systems is essential in some applications, there is a lack of such guidelines for different anchor types, when to anchor, or how to space anchors. This issue is currently being addressed by an ACI 440 task force. In addition to anchor guidelines, guidelines and standards on backbone curves of FR retrofitted components, whether new or existing, are needed. There is also a need for knowledge transfer between the leading SDOs on this research topic, such as the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials (AASHTO), and the International Building Code (IBC). A study by Abdulrahman and Aziz [66] addressed this research need of determination of differences across different design guidelines and standards by performing a comparative study on FRP retrofitted slabs designed with different guidelines. The authors noted the differences in the equations used, and how those differences translate to the ability to predict finite element model results. More studies like this and coordination between S/dos in warranted.

b. Experimental studies of FR composite retrofitted structures that provide knowledge to improve design and evaluation standards and guidelines. Several potential studies were discussed in the workshop, including retrofitted shear walls with and without anchors, low-cycle fatigue testing of FR composite systems in conjunction with other components, and testing of retrofitted diaphragms, including collectors and chords. Testing of different loading protocols was discussed as a research priority, as well as a systematic study of different anchor configurations. Finally, another experimental research need was the testing of retrofitted components up to the point of failure to improve collapse analysis of structures.

IMPLEMENTATION OF RESEARCH NEEDS FOR FR COMPOSITES IN INFRASTRUCTURE

The research needs identified in the literature review and the stakeholder workshop cover a wide spectrum of expertise and effort. Addressing these needs will require involvement from multiple parties, including government agencies, industry, academia, and standards development organizations. The authors of this paper ("NIST research team") identified three key research needs shown on Fig. 5 that they are currently investigating, specifically: 1) determining the durability of FRP composites bonded to concrete substrate using accelerated and outdoor weathering with the goal of using relevant weathering conditions that closely simulate field conditions and failure modes, 2) developing modeling parameters and a testing program for FRP-retrofitted reinforced concrete shear walls, and 3) improving and developing inspection test methods. These research areas will address several needs that received the Highest ranking in the workshop, including: 1) establishment of correlations between laboratory accelerated conditioning test results and field exposure results, 2) structural-scale testing, and 3) improvement of current test methods (QA/QC) to reduce uncertainty in test results for initial performance. It is acknowledged that the NIST research team cannot address all of the aforementioned research needs internally, and this paper as well as the NIST SP 1224 are intended to offer guidance to other researchers on the most pressing needs and a way forward to advance the knowledge of FRP-retrofitted systems.

CONCLUSION

NIST conducted a thorough literature review on the state-of-the-art and state-of-practice on FR composites and FRP-retrofitted buildings and infrastructure. Despite evidence of the extensive research conducted on various aspects of FR composites systems and retrofitted structures, further research is needed to improve the understanding of the initial and long-term performance of FRP-retrofitted structures. This conclusion was confirmed during a stakeholder workshop convened by NIST, where detailed research needs were identified and ranked according to the urgency and expediency the research need means to the advancement and understanding of the use of FRP composites in civil infrastructure. Below is a list of the research needs ranked as Highest during the workshop:

Material Performance of Externally Bonded FR Composites

- Development of criteria for FRP composite materials selection for non-concrete substrate (e.g. steel, timber) application
- Improvement of current test methods (quality assurance/quality control, QA/QC) to reduce uncertainty in test results for determining the initial performance

- Establishment of correlations between laboratory accelerated conditioning test results and field exposure results
- Establishment of inspection protocols and indicators of degradation
- Identification of bond degradation mechanisms between FRP composites and substrates in various environments
- Development of guidelines and certifications for installations
- Development of metrology for fire rating of FRP composites
- Development of round robin tests and establishment of improved correlations between small-scale and structural-scale tests

Structural Performance of FR Composite Retrofitted Structures

- Testing at large structural scale, particularly diaphragms, shear walls, and large structural assemblies
- Improvement of inspection practices, including guidelines for inspectors, and measurement science tools for in-situ field testing
- Development and validation of models that consider aging and accumulation of damage from minor events
- Development of design standards and guidelines
- Experimental research on FR composite retrofitted structural components and buildings

NIST has compiled and published Special Publication SP-1244 [2] that details the literature review and results from the relevant workshop in further detail. The goal of this paper and the NIST SP is to serve as a roadmap to inform diverse research plans developed by stakeholders, which include NIST, other government agencies, universities, private industry, and other organizations involved in advancing the use of FR composites for repair and retrofit of buildings and infrastructure. Further investigation by stakeholders of the research needs and those identified in the report will ultimately help develop and enhance FR composite performance and state-of-practice for the nation's built environment.

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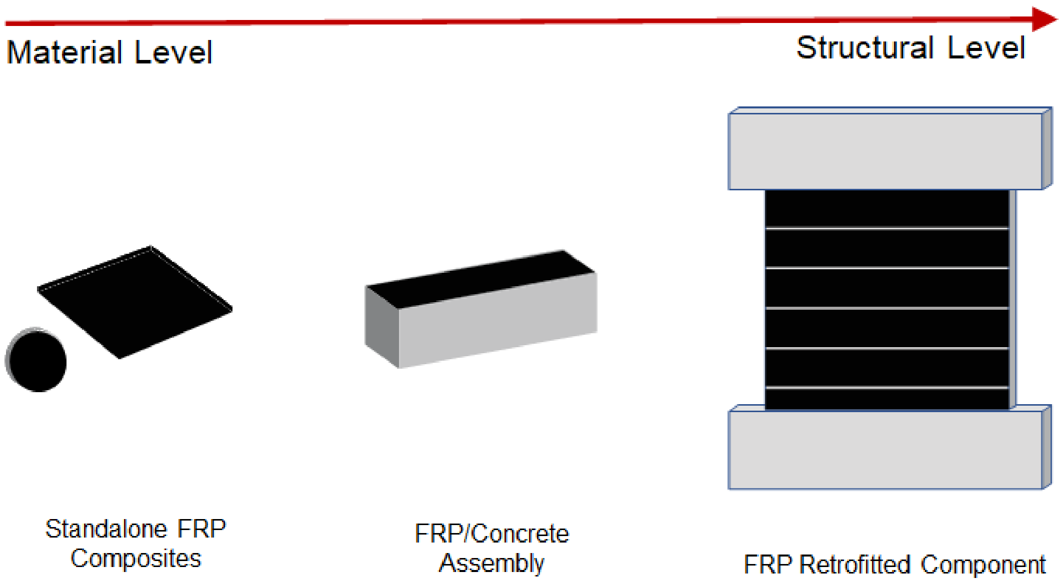

Fig. 1—The three FRP scales of interest: FRP composites, FRP/concrete assemblies, and FRP-retrofitted components

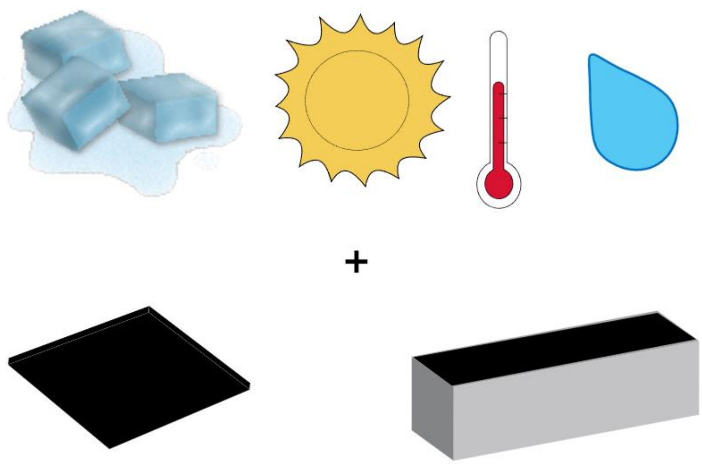

Fig. 2—Environmental conditions (top) that may be applied to FRP (bottom left) and FRP assemblies (bottom right) for durability assessment

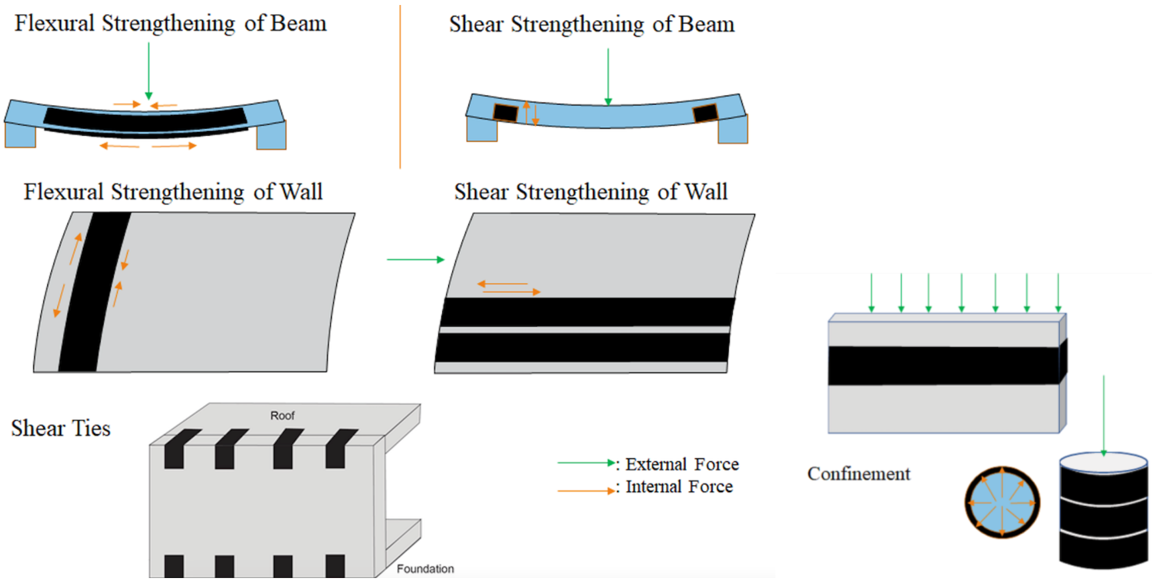

Fig. 3—Illustration of various types of FRP applications to different structural components

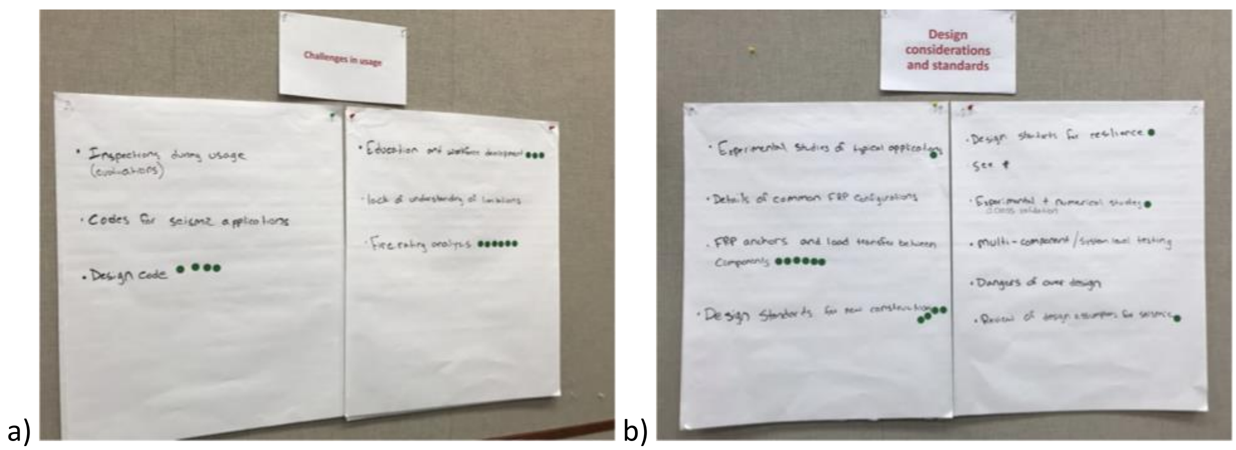

Fig. 4—Examples of the notes taken during the breakout sessions of the workshop and the method of voting for most important research needs: (a) challenges in usage in materials selection; (b) design considerations and standards for structural performance

Fig. 5—Research needs addressed by the NIST research team: (a) durability evaluation; (b) inspection techniques; and (c) performance of FRP-retrofitted components