

# International Workshop on Aging of FRP Composites

## Final Report

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Exploratory Advanced Research Program  
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McLean, VA 22101

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International Workshop on Aging of FRP Composites  
September 25-26, 2013 - Ashburn, VA

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## EXECUTIVE SUMMARY

Since the early 1980s, U.S. Department of Transportation's Federal Highway Administration (USDOT-FHWA) has played a lead role in promoting and advancing Fiber Reinforced Polymer (FRP) composites applications for highways and bridges. Understanding the durability response of polymer composite materials in terms of their aging mechanisms through material degradation at pico, micro, and meso levels is critical for safe and economical field implementation of FRPs.

Thirty-five experts from the field of advanced transportation materials, including researchers, designers, and owners, were invited to attend an international workshop titled "Aging of FRP Composites". The workshop was sponsored by the Exploratory Advanced Research (EAR) Program of the Federal Highway Administration (USDOT-FHWA) through a National Science Foundation (NSF) grant IIP-1230351. The workshop was held on September 25 and 26, 2013 at the National Transportation Safety Board Training Center, Ashburn, VA.

The objectives of the Workshop were as follows: (1) Discuss and summarize the state-of-the-art knowledge on the aging behavior of FRPs for infrastructural applications; (2) Open discussions on FRP material and component resistance factors based on available data; (3) Suggest effective methods to collect additional data and procedures to refine and integrate all the available information in literature; and (4) Identify research needs for future research, development, and evaluation programs dealing with durability and design issues leading to realistic design, construction, evaluation and rehabilitation guidelines for infrastructure systems.

The workshop began with plenary presentations by the invited experts to provide up-to-date information regarding the science on the aging of composites, followed by four parallel working group discussions. The four groups were: Group A - FRP Internal and External Reinforcement, Group B - FRP Shapes, Group C - Test Methods, and Group D - Material Degradation and Life Prediction Models. Each group addressed the following: 1) What is the state-of-the-art? 2) What are the barriers for FRP composites to be more fully utilized in infrastructure? 3) What research can break down these barriers? and 4) Where should the research, development and implementation priorities lie?

On the second day of the workshop, the group discussion summaries were presented by group chairs to all workshop participants for further discussions and possible modifications. Finally, workshop participants identified high priority future research topics in terms of their importance and impact. The workshop participants concluded that FRP long-term structural performance evaluation is needed by collecting and evaluating samples from in-service structural components and systems for their thermo-mechanical property degradation. Such data along with life prediction models coupled with the laboratory-based accelerated aging data would allow accurate life cycle assessment of FRPs.

**Key words:** Durability, aging, FRP, composites, research needs, infrastructure system

## STEERING COMMITTEE

Gangarao Hota, West Virginia University: Co-Chair  
Louis Triandafilou, Federal Highway Administration: Co-Chair  
Ruifeng (Ray) Liang, West Virginia University  
Charles Bakis, Penn State University  
Donald Williams, West Virginia Department of Transportation  
Mario Paredes, Florida Department of Transportation  
Mark Skidmore, West Virginia University

## ACKNOWLEDGEMENTS

The Steering Committee and the West Virginia University Constructed Facilities Center are grateful to the Exploratory Advanced Research (EAR) Program of the U.S. Department of Transportation - Federal Highway Administration (USDOT-FHWA) through the National Science Foundation (NSF) grant IIP-1230351 for providing the funding for the workshop. We also want to thank all the participants for taking the time out of their busy schedules to participate in this workshop. In particular, we would like to thank Chairs of four working groups (Dr. Brahim Benmokrane for Group A - FRP Internal and External Reinforcement, Dr. David Scott for Group B - FRP Shapes, Dr. Ellen Lackey for Group C - Test Methods, and Dr. Charles Bakis for Group D - Material Degradation and Life Prediction Models) for leading productive and fruitful discussions.

A draft final report had gone through several rounds of review and revision by the workshop participants, before arriving at this final report. Initially, a draft final report was submitted to the Exploratory Advanced Research Program of USDOT-FHWA on October 28, 2013. Based on the review comments of USDOT-FHWA, a revised draft final report was sent to all workshop participants for review, clarification, and modification on January 14, 2014. After integrating the comments from the workshop participants, revised final report was sent to the Working Group chairs and Steering Committee members for finalization on February 10, 2014. Then the final report reflecting new corrections from the group chairs was sent to the Steering Committee members for approval on February 14, 2014 and submitted to USDOT-FHWA on Feb 17. The authors of the report would like to thank all the reviewers for their time and constructive comments during the development of this report. This report is available at the workshop website: <http://www.statler.wvu.edu/cfc/research/projects/aging.php>

Any opinions, findings, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration or National Science Foundation.

# SUMMARY REPORT

## 1. Introduction

For the past three decades fiber reinforced polymer (FRP) composites have been gaining acceptance, albeit slowly, as advanced and durable materials for infrastructural applications including structures for highways, railways, and waterways, utility poles, wind turbine blades, and pipelines. For example, hundreds of pedestrian and vehicular bridges have been built worldwide using FRP composite materials. In addition, thousands of concrete and timber bridges have been rehabilitated using FRP composite wraps. The USDOT-FHWA has been playing a lead role in promoting and advancing FRP applications for highways and bridges since the 1980s. Through the Transportation Equity Act for the 21st Century (TEA-21), 37 demonstration projects were funded for the use of FRP composites in bridge decks and superstructures, and many more were repaired and rehabilitated using state or county funding. However, some of these structures may have been under-designed or over-designed due to an inadequate understanding of the durability of FRP materials.

As per ACI440L, durability of FRP is defined as its ability to resist cracking, oxidation, chemical degradation, debonding, wear, fatigue, and the effects of damage from foreign objects for a specified period of time under appropriate load conditions and under service exposure conditions. However, this report prefers to replace the word “resist” from the ACI 440L definition to “minimize”.

Therefore, understanding the durability response of composite materials in terms of their degradation mechanisms is critical for safe and economical mass field implementation of FRPs. Such understanding and accurate determination of resistance factors for FRP composites designs might be accomplished by conducting accelerated aging tests on composites under controlled laboratory conditions and arriving at an appropriate rate of degradation based on the field data to be collected from in-service FRP composite bridges and other infrastructure systems.

After about 30 years in service, it is time to evaluate the performance of FRP structures by collecting field samples and test for property degradation of those in-service structural components and systems. Such data along with the accelerated aging data from laboratory tests (being funded by National Science Foundation (NSF)) and life prediction models hopefully lead to accurate life cycle assessment of FRPs. In addition, with ever increasing attention towards a sustainable built-environment, FRP composites have a great potential, as a sustainable material of high strength to weight ratio, to design durable, efficient, and safer infrastructure systems. Durability data of FRPs will help facilitate this trend.

To further assess the state-of-the-art understanding of aging of composites and effectively establish a research, development and evaluation program (roadmap) dealing with durability and design issues of FRP composites, a two-day workshop of leading scientists and engineers was supported by the Exploratory Advanced Research (EAR) Program of the Federal Highway Administration (USDOT-FHWA) through a NSF grant IIP-1230351.

## **2. Workshop Program**

### **2.1 Objectives of Workshop**

The main objectives of the workshop on FRP composites were: 1) To give a state-of-the-art overview of current worldwide research on the aging/durability behavior of composite materials for civil and military infrastructural applications, 2) To suggest effective methods to collect additional data and procedures to integrate all the readily available information, 3) To focus on FRP composite coupon and component resistance factors based on available data, and 4) To effectively establish a research, development and evaluation program dealing with durability issues and design guidelines for infrastructure systems.

### **2.2 Workshop Chairs and Steering Committee**

The concept of organizing such a workshop was initiated by Dr. Gangarao Hota and Mr. Louis Triandafilou who served as co-chairs of the Workshop. A steering committee was assembled to guide the planning of the Workshop. The steering committee consisted of:

- Dr. Gangarao Hota, West Virginia University: Co-Chair
- Mr. Louis N. Triandafilou, USDOT-Federal Highway Administration: Co-Chair
- Dr. Ruifeng (Ray) Liang, West Virginia University
- Dr. Charles Bakis, Penn State University
- Mr. Donald Williams, West Virginia Department of Transportation
- Mr. Mario Paredes, Florida Department of Transportation
- Mr. Mark Skidmore, West Virginia University

### **2.3 Workshop Support**

The workshop was sponsored by the Exploratory Advanced Research (EAR) Program of the Federal Highway Administration (USDOT-FHWA) through a National Science Foundation (NSF) grant IIP-1230351. Additional support to the organizing effort was provided by the West Virginia University's Constructed Facilities Center.

### **2.4 Venue**

The workshop took place on September 25 and 26, 2013, at the National Transportation Safety Board Training Center (NTSBTC), 45065 Riverside Pkwy, Ashburn, Virginia 20147 which is located on the Virginia campus of The George Washington University. This is a recently established facility owned and operated by the U.S. Department of Commerce.

### **2.5 Participants**

Attendance at this workshop was by invitation only for a target audience of approximately 35 participants including representatives from the international community. Each attendee was invited to highlight their current understanding and research needs on aging of FRP composites. 36 invitations were sent out to U.S. based leading researchers, designers, and owners of



infrastructure systems with advanced FRP composite materials and out of these 36 invitations, 27 were available to accept the invitations. Similarly, 14 invitations were sent to FRP aging experts outside the U.S but only 8 international experts were able to attend the workshop. While selecting the workshop participants, attention was paid to maintain a balance between researchers that focus their work on FRP (external and internal) reinforcement and those that specialize in prefabricated FRP shapes. The American Composites Manufacturers Association (ACMA) was invited to represent the FRP industry. The Workshop was conducted with 35 participants including the program directors from FHWA. Table 1 summarizes the breakdown of participant affiliations and nationalities. A complete participant list is included in Appendix A.

**Table 1 Workshop Participants Breakdown**

<b>By Sector</b>	
Academia	24
State DOTs	6
Industry	1
Government Administration and Labs	4
<b>By Country</b>	
United States of America	27
Australia	1
Canada	1
China	1
France	1
Hong Kong, China	1
Italy	1
Japan	1
UK	1

Participants were divided into four (4) working groups for parallel brainstorming discussions as follows:

- Group A: FRP Internal and External Reinforcement
- Group B: FRP Shapes
- Group C: Test Methods
- Group D: Material Degradation and Life Prediction Models

Group chairs were selected by the Steering Committee for their leadership in, and knowledge of, the group topics. Participant’s group attendance is listed as Appendix B.

## 2.6 Workshop Agenda

The Workshop agenda is given in Appendix C. The meeting was called to order at 8:15 a.m. on September 25<sup>th</sup> by the workshop co-chair Mr. Louis N. Triandafilou, followed with a welcome speech by Mr. Jorge E. Pagán-Ortiz, Director of Office of Infrastructure Research and Development, USDOT-FHWA. The opening speech of Mr. Pagán-Ortiz is given in Appendix D.

Then the workshop co-chair Dr. Gangarao Hota introduced the objectives and scope of the workshop before beginning of plenary presentations by invited speakers. Each presentation was limited to approximately 10 minutes including a brief Q&A session. The presentations were required to highlight one or more of the following: 1) Overview of critical areas of durability, 2) Aging data available, 3) Methods of assessing durability issues of FRPs, and 4) Durability design and acceptance criteria and conclude with “Areas in need of further research”. A total of 23 presentations were given covering a wide range of topics related to FRP aging.

Parallel group discussions started at 2:15 p.m. Each group, under leadership of the Group Chair, was requested to discuss and examine the topics in the following guidelines:

- 1) What is the state-of-the-art?
  - a. Based primarily on the presentations from the morning sessions.
  - b. Group should come to a consensus understanding of the topic area in terms of the currently available research.
- 2) What are the barriers for FRP composites to be more fully utilized in infrastructure?
  - a. Identify specific issues that have been referenced as hindering implementation.
  - b. Although widespread issues are of the utmost importance, unique issues should be noted for completeness.
- 3) What research can break down these barriers?
  - a. Considering the gaps in current research, what new studies can be undertaken?
  - b. Do the issues lie in more of the same research (additional case studies)?
  - c. What are the most likely funding sources?
- 4) Where should the priorities lie?
  - a. Which research projects would have the most immediate impact?
  - b. What is the size of the market for each study?

The above discussions ended at 5:00 p.m. on September 25, 2013. Each group chair was instructed to prepare a summary of their group consensus to be presented in the Plenary Summaries Session.

Plenary Summaries Session took place from 8:00 a.m. – noon on September 26<sup>th</sup>. Each group chair gave a presentation of outcomes from the previous day’s parallel discussions to the whole workshop. More discussions took place from the participants. Group reports are given in next section of the present report.

The research needs from all groups using the information presented in the morning of September 26<sup>th</sup> were integrated and prioritized in terms of their importance and impact on composites infrastructure during Plenary Discussion session in the afternoon of September 26<sup>th</sup>. Research Priorities/Recommendations from this session are presented in Section 4 of this report. The workshop was adjourned at 4:00 p.m. A few snapshots of the workshop activities are shown in Figures 1 to 7.



**Figure 1. Mr. Jorge Pagán-Ortiz of USDOT-FHWA giving an opening speech on the morning of September 25<sup>th</sup>, followed by plenary presentations session.**



**Figure 2. Working Group A, led by Dr. Brahim Benmokrane, discussing the state-of-the-art and research needs in the area of FRP Internal and External Reinforcement on the afternoon of September 25<sup>th</sup>.**



**Figure 3. Working Group B of FRP Shapes, chaired by Dr. David Scott, in session on the afternoon of September 25<sup>th</sup>.**



**Figure 4. Dr. Ellen Lackey, chairing Working Group C on Test Methods on the afternoon of September 25<sup>th</sup>.**



**Figure 5. Dr. Charles Bakis led Working Group D to address the topics on Material Degradation and Life Prediction Models.**



**Figure 6. Mr. David Kuehn addressing questions from workshop participants on the morning of September 26<sup>th</sup>, followed by plenary summaries session.**



**Figure 7. Workshop co-Chairs Lou Triandafilou and Gangarao Hota commending the participants for a productive and successful two-day workshop on the afternoon of September 26<sup>th</sup>.**

## 2.7 Plenary Presentations

Invited speakers through their plenary presentations summarized their current understanding and research activities on the subject of durability/aging of FRP composites. These highlights provided the basis for the workshop participants to develop the state-of-the-art reports. Similarly, each presentation also identified the areas in need of further research as per the understanding of the durability of FRP composites. These materials facilitated the discussions among the workshop participants in an effective and efficient manner to develop future R&D directions (roadmap).

There are a total of 23 presentations, including 12 by university researchers from the United States, 8 from foreign universities, and 3 by engineers from state DOTs. Table 2 shows the breakdown of the plenary presentations by speaker affiliations and working groups. Each title of presentation is listed in Table 3, while the power point slides of these presentations have been published as part of the proceedings of the workshop that can be downloaded from the workshop website: <http://www.statler.wvu.edu/cfc/research/projects/aging.php>.

**Table 2 Plenary Presentations Breakdown**

	University Researchers from U.S.	University Researchers from outside U.S.	Engineers from State DOTs	Sub-total
Group A FRP Reinforcements	2	3	1	6
Group B FRP Shapes	3	2	1	6
Group C Test Methods	3	2	1	6
Group D Mechanisms and Models	4	1	0	5
Sub total	12	8	3	Total: 23

**Table 3 List of Titles of Plenary Presentations**

Title of Presentation	Speaker and Affiliation
<b>Group A: FRP Internal and External Reinforcements</b>	
<i>Chair: Brahim Benmokrane, University of Sherbrooke, Canada</i>	
Moisture Conditioning of Bonded FRP Composites	Trey Hamilton University of Florida, FL
Field Performance of FRP Repair Materials: The Need for More Data	Rebecca Atadero Colorado State University, CO
Durability Issues of FRPs for Civil Infrastructure	Brahim Benmokrane University of Sherbrooke, Canada
Aging of Composites of External Bonded CFRP for RC Structures Strengthening	Emmanuel Ferrier University of Lyon, France
Durability Issues of Concrete Structures Strengthened with Externally Bonded FRP (EB-FRP) Composites	Jian-Guo Dai Hong Kong Polytechnic Univ., China
Oregon DOT Experience with FRP	Bruce Johnson Oregon DOT, OR
<b>Group B: FRP Shapes</b>	
<i>Chair: David Scott, Georgia Institute of Technology, GA</i>	
Aging Studies of FRP Composites at WVU-CFC	Ruifeng Liang and Gangarao Hota West Virginia University, WV
Composite Anti-Collision Bumper Systems and Their Durability under Multi-Environmental Factors	Weiqing Liu Nanjing Tech University, China
Creep of Pultruded Fiber Reinforced Polymeric Materials in Civil Infrastructure Applications	David Scott Georgia Institute of Technology, GA

Aging and Durability Issues of Wood Polymer Composites	Douglas Gardner University of Maine, ME
Review of Fiber Composite Structures in Australia	Thiru Aravinthan Univ. Southern Queensland, Australia
FRP Composites in Texas Infrastructure – How Long Will They Perform?	Tim Bradberry Texas DOT, TX
<b>Group C: Test Methods</b> <i>Chair: Ellen Lackey, University of Mississippi, MS</i>	
Fire Performance of Transportation Structures Incorporating FRP	Venkatesh Kodur Michigan State University, MI
Advanced Test Methods for Evaluating the Durability Performance of FRP Materials	Mohamed PourGhaz North Carolina State University, NC
Determining Characteristic Value of Pultruded Composites Exposed to Environmental Conditioning for Use with the LRFD Standard	Ellen Lackey University of Mississippi, MS
Accelerated Testing Methodology for Long-Term Life Prediction of Polymer Composites	Masayuki Nakada Kanazawa Inst. of Technology, Japan
Compressive Behavior of Composites: Laboratory-based Accelerated Ageing	Costantinos Soutis University of Manchester, U.K.
FDOT's Experience with Material Durability and Its Application to Polymers	Mario Paredes Florida DOT, FL
<b>Group D: Material Degradation and Life Prediction Models</b> <i>Chair: Charles Bakis, Penn State University, PA</i>	
Aging Mechanisms in Polymers and Their Composites: Molecular Level Responses	Rakesh Gupta West Virginia University, WV
Durability of FRP: The Key Role of Cold-cured Thermosetting Resins	Mariaenrica Frigione University of Salento, Italy
Variable Amplitude Fatigue Lifetime Predictions for FRP Composites	Scott Case Virginia Tech, VA
Aging and Durability Modeling Issues for Fiber Reinforced Polymers	Samit Roy University of Alabama, AL
A Model to Predict the Degradation of FRP Bonded Concrete Joints in Moist Environment	Baolin Wan Marquette University, WI

### 3. Group Reports

The following are the reports of four working groups as a result of parallel group discussions.

#### 3.1 FRP Internal and External Reinforcement

##### Participants:

Brahim Benmokrane, University Sherbrooke, Canada: Group Chair  
Rebecca Atadero, Colorado State University, CO



Jian-Guo Dai, Hong Kong Polytechnic University, China  
Emmanuel Ferrier, University of Lyon, France  
Trey Hamilton, University of Florida, FL  
Bruce Johnson, Oregon DOT, OR  
Louis Triandafilou, USDOT-FHWA  
P.V. Vijay, West Virginia University, WV

### 3.1.1 Definition of “FRP Reinforcement”

This group focused on internal and external FRP reinforcement as defined below:

**Internal FRP Reinforcements** made with glass, carbon and basalt were considered. Regular (straight) and bent bars were discussed.

**External FRP Reinforcement** includes primarily bond-critical applications, although some of this also applies to contact critical. Near-surface mounted (NSM) reinforcement was included in the external reinforcement.

**Prestressing Carbon FRP Tendons** were also discussed (pretension and post-tension applications for concrete structures).

### 3.1.2 The State-of-the-Art

#### **All Systems (Internal and External):**

- Currently a number of test methods exist that can be used to assess FRP durability including moisture, UV, alkaline environment, saltwater, creep/sustained stress, heat, freeze-thaw, chemical resistance, fatigue. Some of these conditions are covered by ASTM test methods.
- Current test methods, however, do not provide an estimated service life, nor do they provide guidance for estimating environmental factors that should be used in design.
- Also more importantly, the synergistic effects (ex., moisture, load, and temperature) are not typically addressed in current testing standards.
- Modes of degradation of internal and external FRP reinforcements are not well understood.
- Test methods and requirements for assessing FRP with high durability are lacking.
- Use of natural fibers and bio-resins (state-of-the-art).

#### **Internal Reinforcement**

AASHTO LRFD bridge deck design specifications are available for use in design and construction. Material specifications are currently available in the U.S. that test bars under accelerated conditions intended to provide quality control. Important environmental conditions include high-alkaline environment. However, durability and mechanism of deterioration of Glass FRP bars in concrete require more research in the lab as well as in the field. Basalt FRP bars present interface problems, extensive research is needed in this area. The durability of the resins and the fibers could be evaluated separately under different chemical environments.

#### **External Reinforcement**

Mechanism of deterioration of adhesive bond between concrete and CFRP is not well-understood including change in failure mode from typical cohesive to adhesive mode in certain cases due to moisture. Fracture mechanics models developed for external reinforcement have typically

ignored this adhesive failure mode and assume that the failure plane passes through the substrate concrete. Scale of investigation has typically focused on full-scale strength rather than multi-scale bond behavior. Local analysis at the interphase could create knowledge necessary to address the durability of bond strength. Important environmental conditions include moisture, temperature, and stress.

### **Prestressing Carbon FRP Tendons**

Long-term creep and relaxation behavior is not well-understood.

## **3.1.3 The Barriers for FRP Composites to Be More Fully Utilized in Infrastructure**

### **Internal Reinforcement**

- Ability to correlate accelerated laboratory tests with field performance.
- Laboratory methods of accelerating deterioration do not necessarily reflect the actual degradation mechanisms.
- Lack of proven tools and methods available to monitor performance of FRP.
- Lack of data on long term durability of bent bars.
- First cost and Life cycle cost analysis.
- Lack of provisions on how to repair concrete structures reinforced with FRP bars.
- Lack of correlation of short term durability tests to long term performance of FRP rebar.

### **External Reinforcement**

- Inability to predict or even estimate service life of FRP repair and repaired structure. This relates to cost-benefit of repair and decision to repair or replace.
- Ability to correlate accelerated laboratory tests with field performance.
- Laboratory methods of accelerating deterioration do not necessarily reflect the actual degradation mechanisms.
- Field evaluation techniques are lacking. Currently using ‘coin tap’ to locate delaminations and/or voids. Digital tap hammer is accurate, but covers very small area. It is impractical to ‘tap’ the whole structure and find debonded locations. Difficult to distinguish debonding from initial voids/defects.
- Under less than ideal curing conditions, effect on the durability and mechanical properties with respect to degree of cure is unknown.
- Lack of long performance history.
- Lack of proven tools and methods available to monitor performance of FRP.
- Lack of guidance available on what field measurements will provide assurance that the system is performing properly and will continue to perform properly. System performance vs. localized measurement of bond strength.
- Effect of full or partial coverage bonded FRP repairs on durability of underlying structure is unknown.
- Construction specific documents and specifications similar to those construction manuals for FRPs are not available.

### **Prestressing Tendons**

- Cost of material.

- Anchorage fabrication requires a high degree of skill and care.
- Incompatible thermal expansion between tendon and concrete.

### 3.1.4 Research Topics to Break Down the Barriers

#### **Internal Reinforcement**

- Evaluation of the synergistic (combined) effects of load, moisture, and temperature on the thermo-mechanical properties of reinforcing bars.
- Development of accelerated aging testing protocols simulating field conditions.
- Testing & development of predictive models (e.g., moisture diffusion and/or permeation, Arrhenius models, fatigue, fire resistance).
- Development of field monitoring, inspection and assessment guidelines for long term performance of FRP materials and structures reinforced with FRP bars.
- Development of carbon nanotube-based sensing for structural health monitoring (dispersed carbon nano-tubes in FRP reinforcing bars).
- Aging of in-service (field) structures to collect field samples and calibrate the field aging parameters (e.g., thermo-mechanical property) with the laboratory-based accelerated aging test data.
- Development of life predictive models for accurate life cycle assessment of FRPs.
- Reliable resistance and environmental factors as function of in-service conditions (temperature, humidity, etc).
- Evaluate the effect of surface texture, configuration, and geometry on durability.
- Conduct durability research on basalt bars.
- Evaluate the long term durability of bent bars.
- Development of new bars using high performance resins with low permeability, and new materials such as nanocomposites.
- The durability performance should be demonstrated using analytical methods and modern techniques for investigation and characterization of material (Scanning Electron Microscope, Fourier Transform Infrared, Differential Scanning Calorimetry, Dynamic Mechanical Analysis, Thermogravimetric Analysis, non-destructive evaluation).
- Research on long term durability of FRP reinforcing bar and develop a consensus on how to correlate such durability with short term tests.
- Better performance consistency of raw materials (basalt fibers).
- Improvement on process and product quality control (in particular bent bars).
- Develop testing program for product approval.
- Research to demonstrate that this material will last 75 years.

#### **External Reinforcement:**

- Development of accelerated aging testing protocols simulating field conditions and natural aging (ACI 440I sub-committee is preparing a guide on this topic).
- Gather data from field studies of actual FRP installations.
- Development and/or enhancement of predictive models.
- Better understanding of the short and long term effect of moisture on bond.
- Effect of incompatible thermal expansion between concrete and FRP.

- Modeling creep for external bonded is not common.
- Multi-scale approach for characterizing and developing a better understanding of the mechanisms of bond and bond degradation.
- Development of moisture-resistant bonding adhesives.
- Specimens should be strengthened and be subjected to freeze thaw exposure in the orientation that reflects field conditions.
- Additional data are needed for combined environmental exposure and fatigue loading.
- Development of field monitoring, inspection and evaluation guidelines for long term performance of FRP materials and structures.
- Development of carbon nanotube-based sensing for structural health monitoring (dispersed carbon nano-tubes in FRP reinforcing bars, tendons, and FRP layers).
- Simple and accurate techniques for field assessment of externally bonded FRP are needed for researchers and bridge inspectors. Current methods may not be practical for whole structure and/or may be only qualitative.
- Using fundamental understanding of bond degradation, develop rational design procedures that incorporate durability of FRP composite.
- Evaluate effect of fabrication (e.g., cutting, drilling through) on long-term durability.
- Evaluate effect of fillers, additives, and voids on long-term durability.
- Evaluate effect of size, shape, extent and region of debonding including debond growth over time on durability.
- Development of inorganic resins for improved fire resistance.

#### **Prestressing CFRP Tendons:**

- Demonstration projects.
- Simplified anchorage details that provide reliable and safe service.
- More research on creep and relaxation.
- Develop specifications and certification of the material to ensure fiber-resin compatibility and long-term performance.

#### **3.1.5 Research Priorities**

- Perceived lack of understanding regarding durability of both internal and external reinforcement may impede their use. Overall priority might be leaning toward both types of reinforcements (internal and external).
- Priority for bridge owners would be to be able to answer the question: “How long will this last?”

#### **Research Needs**

- IR 1: Data from aging of in-service (field) structures and laboratory accelerated aging test data to develop predictive models (e.g., moisture diffusion and/or permeation, Arrhenius models, fatigue).
- IR 2: Evaluation of the synergistic (combined) effects of load, moisture, and temperature on the thermo-mechanical properties of reinforcing bars.

- ER 1: Development of simple and accurate techniques for field monitoring, inspection and evaluation guidelines for long term performance of FRP materials and structures.
- ER 2: Multi-scale approach for characterizing and developing a better understanding of the mechanisms of bond and bond degradation due to moisture.
- Prestress: Develop specifications and certification of the material to ensure fiber-resin compatibility and long-term performance.

## 3.2 FRP Shapes

### Participants:

David Scott, Georgia Institute of Technology, GA: Group Chair

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### 3.2.1 Definition of an “FRP Shape”

A manufactured, stand alone, load carrying structural element used in applications related to transportation infrastructure. Discussions also covered structural systems using FRP shapes. Discussions excluded FRP reinforcing bars and wraps.

Manufacturing Processes included in Group B discussions:

- Pultrusion: A highly automated continuous mass manufacturing of resin-impregnated fiber reinforced composites at speeds ranging from 1” to 60” per minute, through a heated die forming the desired cross-section and curing the resin. This process produces structural composites of high strength, stiffness and fiber volume at moderate capital equipment costs.
- Filament Winding: A process where continuous fiber filaments, called rovings, are saturated with catalyzed resin and helically wound around a mandrel, yielding a high fiber-to-resin ratio part. The fibers are fed through a device which moves up and down the length of rotating mandrel.
- VARTM: Vacuum-Assisted Resin Transfer Molding is a batch process typically using one-sided tooling and vacuum bagging for large-scale FRP parts. This process cures the resin without applying heat and is usually labor intensive.
- Compression Molding: A batch process consisting of placing a charge in the mold, which is subsequently closed and held at a high pressure, and then heating the mold to initiate cure reaction.

### 3.2.2 The State-of-the-Art Related to FRP Shapes

*A matter of perspective:*

**End Users:** The technology is still in the experimental stage, and has shown very poor performance and little reliability to date.

The above statement is mainly based on direct statements from State DOT personnel, as well as inferred opinions based on the experience of other researchers. However exceptions exist with FRP sign structures repairs and hybrid structures used in Maine. Other countries (e.g. South Korea) appear to have exhibited greater acceptance for transportation infrastructure applications.

**Manufacturers:** Failures in several demonstration projects related to bridge decks indicate that work needs to be done before FRP shapes are more broadly accepted in this area. Other applications have been more successful - trusses for pedestrian bridges, girders, poles, and other structural elements. Numerous companies were out of business due to inability to go from R&D to market. Also there is a disconnect between “laboratory” and “field” R&D.

**Research Professionals:** The technology is beyond the “demonstration project” stage. That being said, the industry still falls short of full marketability as a viable alternative to traditional structural materials and systems. Some areas (truss elements) are more “mature” than others (e.g., bridge decks). There is a distinct lack of understanding at the SYSTEM level.

### 3.2.3 The Barriers Hindering Wider Usage of FRP Shapes

- COSTS - First cost versus life cycle cost modeling and acceptance procedures.
- Education and training of engineers, contractors, and other technical professionals on the use of FRP materials and systems.
- Inability to accurately simulate field conditions in the laboratory.
- Examples of more specific technical issues:
  - Lack of ASTM test methods to support design guidelines and standards.
  - Lack of consensus understanding of primary limit states such as flexure, torsion.
  - Lack of consensus understanding related to design of connections.
  - Perception of structural behavior as linear elastic to catastrophic failure, even though new structural layouts mitigate this problem.
  - Development and calibration of resistance factors, and continued debate on the applicability of these factors based on manufacturing process, etc.
  - Lack of useful construction standards and specifications.
  - Lack of useful inspection standards and specifications.
    - QA/QC during manufacture.
    - Inspection during construction.
    - Periodic performance reviews - Service life inspection after the product is built.

### 3.2.4 Research Topics to Break down the Barriers for FRP Shapes

- Correlate short-term durability lab test response to long-term field performance (ASTM).
- Investigation of synergistic effects on long-term performance.
  - Temperature, moisture, and static + fatigue loads.
- Potential knowledge transfer from other industries to civil infrastructure.

- Rigorous assessment of critical parameters including manufacturing process, constituent make-up (materials), and layup on long term performance.
- Mechanisms of deterioration (reduction of strength, stiffness, and durability) at micro, meso, macro levels.
- Standardize data collection after harvesting samples from in-service structures.
- Establish minimum performance requirements related to durability.
- Development of a searchable knowledge database of both laboratory and field tests and experimentation results.
- Service life prediction models and life cycle assessment.

### 3.2.5 Research Priorities

- Correlate short-term durability lab test response to long-term field performance (ASTM).
- Investigation of synergistic effects on long-term performance.
  - Temperature, moisture, and static + fatigue loads.
- Rigorous assessment of critical parameters including manufacturing process, constituent make-up (materials), and layup on long term performance.
- Mechanisms of deterioration (reduction of strength, stiffness, and durability) at micro, meso, macro levels.
- Service life prediction models and life cycle assessment.

### 3.3 Test Methods

#### Participants:

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#### 3.3.1 Areas of Focus

This group focused on the following discussion topics:

- **Assessment of current standard test methods including** coupons, components, systems under static, dynamic, fatigue, creep, thermal and fire.
- **Accelerated testing methodology (ATM).**
- **Field data collection methods of in-service FRP structures.**

#### 3.3.2 Current State of the Art

- A variety of standards and in-house procedures exist and are commonly used today. Some standards developed for metals, concrete, or other materials have been adapted for use with FRP.

- Literature data is often difficult to compare due to variation in the procedures used to obtain the data.
- Currently the connection between laboratory and field data is limited.
- Current standard test methods do exist (ASTM, ACI, international, etc.) but they should be cataloged and compared.
- Nondestructive test methods are well-established for traditional infrastructure materials such as concrete and steel as standard test methods (such as ASTM) and recommended practices (e.g., RILEM) are available and are used in the laboratory and in the field.
- Nondestructive test methods such as ultrasonic and impact echo methods are used in laboratory and the field for FRP infrastructure materials. Current field test methods for infrastructure FRP materials rely on visual inspection and acoustic tap techniques. Recently, infrared (IR) thermography has been gaining popularity among infrastructure owners and operators. However, standard test methods and recommended practices for these nondestructive test methods are not available. Furthermore, the limitations of these nondestructive test methods as it relates to FRP materials and structures inspections are not well-documented.
- Fire resistance of structural member is evaluated through standardized test method for different members such as columns, beams, slabs, floors etc. These methods are specified in standards such as ASTM E119, ASTM 1529, UL 263, UL 1592 and NFPA standards.
- The above fire test methods were originally developed for steel, concrete, masonry and wood members. However, the application of these methods for FRP structures needs to be updated to account for different test conditions (ex: fire exposure, time of testing), loading level and limiting states (failure criterion).
- Flame spread ratings and smoke classification ratings are done at material (FRP) level and the limits for this are given in building codes and/or fire codes. The test methods for this are established and there are standards for testing these are available in ASTM, NFPA and UL documents.
- There is information on test procedures and data on different composites that can be borrowed for other fields such as aircraft industry and naval industry.

### 3.3.3 The Barriers Hindering Development of New Test Methods

- Buy-in from interested parties.
- Studies are needed to understand the test parameters that need to be standardized.
- Support is needed to conduct round-robin testing.
- Champions are needed to shepherd the methods through the standardization process.

### 3.3.4 Research Topics for New Test Methods

#### Standardization of Basic Durability Test Methods

- Standardization of basic environmental characterization methods such as freeze/thaw, moisture exposure, creep, chemical exposure (deicing solutions, salt water, fuels, chemical plants, etc), and long term viscoelastic properties is needed.
- Practical and economical test methods are desired.



- Sample locations and sample preparation should be considered.
- Influence of manufacturing process and cure of the composites being characterized should be considered.
- Necessary to establish basic material comparison properties and for the population of material databases.
- Development of methods applicable for material level characterization, structural level, and joints. ASTM standard procedures will be most applicable at the materials level, as structures will likely require more specialized testing.

## **Fire Test Methods**

### Material Level Characterization

- Limited data is currently available for non-aged/non-damaged material properties of FRP under fire conditions for long durations.
- Standardized test procedures need to be developed so results from various sources can be compared.
- It may be possible to extend test methods now available for steel or concrete as a basis to develop these standardized test procedures for characterization under fire conditions.

### Structural Level Characterization

- ASTM E119 (Standard Test Methods for Fire Tests of Building Construction and Materials) exists for structural level characterization, but realistic failure need to be established.
- Smoke toxicity and flame spread test methods currently exist but most were developed for aircraft or naval applications for evaluation of short term exposure. Infrastructure applications are more concerned about strength requirements for 1-2 hours under these conditions. Procedures that examine these property requirements for infrastructure are needed.
- In order to develop calculation methods for evaluating fire resistance of structural members, the properties of FRP reinforcement (in addition to concrete and steel reinforcement) needs to be known in the temperature range of 20<sup>0</sup>C-800<sup>0</sup>C.
- The properties that are of interest are thermal properties (thermal conductivity, specific heat, mass loss), mechanical properties (tensile strength, bond strength, stress-strain response, modulus), deformation properties (thermal expansion, creep). All these properties vary with temperature and are also specific to composition of FRP and epoxy and to curing conditions (temperature and time).

## **Comparison of Field Data and Lab Data**

- Field data is desired by many DOTs.
- Correlation of coupon property data to data at the structural level is needed under both laboratory conditions and under field conditions.
- Standardized test methods to characterize field installations for aspects such as bond quality, void content, effect of various environments. Questions include how best to evaluate bond

quality, void content, and max void size. Questions to be answered by this include those about installation quality, influence of qualified operators for installation, size effects.

- NDE may be used to compare field and lab data prior to and after aging to quantify the aging. NDE test methods are not mature enough at this time to be able to do this, but a development project to get to this point would be desirable.
- Possible need for the utilization of a benchmark location for natural aging of samples via outdoor exposure testing. Example is the utilization of South Florida for weathering exposure to heat, UV, and moisture. ASTM G50-10 Standard Practice for Conducting Atmospheric Corrosion Tests on Metals and ASTM G92-86(2010) Standard Practice for Characterization of Atmospheric Test Sites could be leveraged to develop these procedures.

#### Questions to be Addressed Concerning How Field Data is Obtained:

- Should field samples be collected from field installations or do you create more damage as you do this? Possible approaches – build in redundant dummy section to field installations to be used for test samples extraction, fabricate field installations with embedded sensors to monitor aging degradation rate data (Question: What data needs to be recorded and how to correlate this with laboratory data?).

#### **Accelerated Test Methods**

- Establish fundamental understanding of the deterioration mechanisms and how acceleration of aging affects the mechanisms of degradation.
- Knowledge of deterioration mechanisms will help develop better acceleration methods and the results of accelerated test methods can be better correlated to naturally aged samples.
- Standardized accelerated test methods need to be developed once this understanding is developed.

#### **Interface Characterization**

- The optimum characteristics for the interface are dependent on the application in question.
- Notch sensitivity can be used to characterize interface properties for the composite system. This is more realistic than using single fiber pull-out testing to characterize the interface properties of the composite system. However, development of a standard test method for notch sensitivity is needed.
- No universally accepted test methods for Mode II fracture toughness exist.
- Effects of environmental exposure on the interfaces need to be characterized and better understood.

#### **3.3.5 Research Priorities**

- Standardization of Basic Durability Test Methods
- Fire Test Methods
- Comparison of Field Data and Lab Data
- Interface Characterization

## 3.4 Material Degradation and Life Prediction Models

### Participants:

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### 3.4.1 Areas of Focus

This group focused on the following discussion topics:

- **Material degradation (mechanistic) models** at all (nano, micro, milli, meso, and macro) levels.
- **Molecular level understanding of material aging** including physical aging and chemical aging.
- **Life prediction models** including remaining life model, fatigue life model, creep model, and combined (temperature, pH , moisture and others) models

### 3.4.2 The State-of-the-Art

- Uncertainties regarding service life estimates.
- Possibly excessive conservative “knockdown factors”
- Usual modeling approach: pick a representative material and model it under certain conditions.
  - Materials are proprietary (limited information).
  - Pick either controlled lab experiments or field experiments.
  - Apply S-N curves, time-temperature superposition principal, Arrhenius relationship.
- Types of degradation are well known, but interactions are not well known.
- Some efforts are aimed at bridging length and time scales.
  - Multi-scale modeling is very computationally intensive.
  - Molecular dynamics force fields are not well defined for polymeric systems, especially when chemical reactions are occurring.

### 3.4.3 The Barriers for Modeling FRP Composites

- Proprietary materials.
- Lack of consistency/completeness of available data.
- Bridge between high fidelity physics models and models accessible by practitioners.
- Lack of funding for modeling efforts.
- Inadequate models for bridging time and size scales.
- Limited computational power for multi-scale modeling.
- Variability in the loads, environments, and material quality/properties.

- e.g., cold-cured resins

### 3.4.4 Suggested Research for Breaking down Barriers for Modeling FRP Composite

- Encourage the use of “model” material systems in research
  - Possible sequential addition of practical additives (e.g., fillers, UV protectant, fire retardant, etc.)
- Develop a database of existing degradation and lifetime data
- Develop bridges between high fidelity physics models and models accessible by practitioners
- Develop stochastic models that include variability of loads, environments, and material quality/properties
- Recommended funding: Pooled NSF & US DOT
  - Enable research on mechanics/chemistry interface
  - Hold workshops to develop links between stakeholders

### 3.4.5 Research Priorities

- Moisture effects (biggest impact)
- Static and cyclic fatigue
- Stress-temperature-chemical interactions
- Major market: bridge repair

## 4. Research Priorities/Recommendations

### 4.1 Research Priorities

At the plenary discussion, the workshop participants from all groups have integrated the research needs identified by each working group and summarized into the following high priority research topics for infrastructure composites:

- Mechanisms of deterioration
  - Reduction of strength, stiffness, and durability at micro, meso, macro levels
  - Multi-scale approach for characterizing and developing a better understanding of the mechanisms of bond degradation due to moisture (biggest impact)
  - Static and cyclic fatigue
- Test Methods and Modeling:
  - Data from aging of in-service (field) structures and laboratory accelerated aging test data to develop predictive models (e.g., moisture diffusion and/or permeation, Arrhenius models, fatigue)
  - Standardization of Basic Durability Test Methods (ASTM)
  - Fire Test Methods
- Investigation of synergistic effects on long-term performance:
  - Temperature, moisture, and static + fatigue loads
  - Degradation mechanism-based (rather than phenomenological) stress-temperature-chemical interactions

- Manufacturing process, constituent make-up (materials), and layup on long term performance
- Correlation of short-term and long-term performance:
  - Relate short-term durability lab test response to long-term field performance
  - Development of simple and accurate techniques for field monitoring, inspection and evaluation guidelines for long term performance of FRP materials and structures
  - Development of a searchable knowledge database of both laboratory and field tests and experimentation results

## 4.2 Recommendations

Based on the above high priority research topics, the workshop participants identified the following topics for consideration of the broader community with interests in funding, conducting research, and supporting uptake of research results for and about the use of FRP materials in highway infrastructure. The topics are not listed in any priority order.

### 4.2.1 Investigation of Synergistic Effects on Long-Term Performance

**Problem Statement:** Majority of in-service FRP composite materials, components and structures are subjected to a variety of environmental (moisture, freeze-thaw, salt, pH, UV, etc.) and loading (bending, tension, shear, dynamic/impact) conditions. Long-term performance evaluations have to be carried out under the above combined factors for realistic and wide ranging field conditions.

**Objective:** To evaluate the material and structural response and arrive at synergistic factors affecting long-term performance of FRP material systems.

**Scope of Work:** Investigate FRP shapes and internal and external FRP reinforcements for concrete under the following factors: stress, chemical reactions, UV, moisture, temperature, and manufacturing process

**Research Significance:** The results will enable us to arrive at more accurate resistance (“knock down”) factors for infrastructural system design.

### 4.2.2 Modeling of Long-Term Performance of FRP Structures Based on Short-Term and Field Test Data

**Problem Statement:** Laboratory tests using accelerated aging methods are commonly used to quality FRP composite materials for long-term use. Accelerated aging tests will have to be designed and carried out with in-depth thought and care to give rise to mechanistic models which must be validated with field data, before developing aging prediction models.

**Objective:** To develop models to predict long-term performance based on short-term laboratory and field test data. Consider synergistic effects as necessary. The focus should be on developing

models based on actual degradation-mechanisms (not on phenomenological models by fitting test data).

**Scope of Work:** Develop mechanistic models, at a minimum, using available data. Collect data to validate the models where suitable data are not available.

**Research Significance:** Currently, long term performance models based on material degradation mechanisms/rates are not available. Development of such models with sufficient understanding of degradation mechanism will help improve the understanding of durability response of FRP composites.

#### 4.2.3 Strategies for Enhancing Bond Performance of Structures Incorporating FRP

**Problem Statement:** Strengthening of structures and damage due to mechanical or environmental effects, especially degradation of bond between substrates and external wraps, necessitates identification of durable and economical FRP repairs. Load or seismic upgrades are often required to meet specification requirements for long service life. Mechanical damage from vehicle collisions and environmental degradation like corrosion and freeze/thaw demand FRP retrofitting.

**Objectives:** To identify basic factors that influence bond between external FRP reinforcement and concrete, steel to FRP, and FRP to FRP.

**Scope of Work:** Develop strategies and methods to improve bonding of external wraps with substrates including surface preparation, resin modification, and innovative design. Develop guidelines for FRP bonding and repair.

**Research Significance:** Bond is critical for achieving the specified system properties like strength and stiffness in a structural member. External bonding of FRP wraps can change the structural response significantly depending on surface conditions, surface preparation, type of FRP, and environmental factors such as temperature, humidity, and curing time. There is limited data on the effect of various factors on the extent of bond strength in FRP strengthened structures.

#### 4.2.4 Standardization of Basic Durability Test Methods for Infrastructure Applications

**Problem Statement:** Lack of standards across the industry continues to contribute to limited usage of FRPs in infrastructure. To alleviate this, a program is desired to establish standardized test methods that will be utilized for DOT projects. The establishment of consistent property measurement techniques will give researchers and practicing engineers a baseline to consistently evaluate the performance of these materials. The availability of standardized durability test methods will also provide data necessary for further development of predictive models for these materials.

**Objectives:** To establish standardized durability test methods so that materials under consideration for infrastructure use may be evaluated and data associated with these materials could be compared consistently within the industry.

**Scope of Work:** Evaluate current test methods, identify necessary property characterization requirements, identify significant test parameters for the various methods, develop documentation necessary for standardization, implement standardization procedures, and conduct round-robin testing. Throughout the standardization process, input from various industry constituents will be sought and integrated to help establish acceptance of the methods. After drafting of such standards, the draft standards will be disseminated to industry personnel for feedback.

**Research Significance:** A literature review will be developed to identify the most needed test methods and select up to 5 methods for standardization. The most significant test parameters for each test method will be identified. Documentation necessary for standardization by an accrediting body such as ASTM will be provided. Intralaboratory and interlaboratory test data for typical FRP materials will be provided. Upon completion of the standardization process, a workshop will be held to introduce new standards to industry personnel to encourage more widespread use.

#### **4.2.5 Effects of Moisture on the Long-term Performance of Externally Bonded FRP Retrofits for Concrete Structures**

**Problem Statement:** A large volume of previous work has demonstrated that deterioration due to moisture will reduce the effectiveness of externally bonded CFRP systems applied to concrete structures. However, this impact has not been quantified in terms of potential loss of performance in the retrofit system.

**Objectives:** The proposed research program seeks to quantify the impact of moisture-related degradation on the performance of externally bonded FRP retrofits.

**Scope of Work:** Development of an experimentally supported degradation mechanism-based model to determine the effect of moisture exposure duration and magnitude on the structural performance of the retrofitted elements. Use field monitoring and data collection to develop a more accurate model of moisture transport mechanisms for in-service structures. Conduct *in-situ* evaluation of structural performance of retrofitted elements where moisture-induced deterioration has been observed. Correlate results from model development, laboratory testing, and field studies to develop a methodology estimating time-dependent effects of moisture-induced deterioration on the expected structural performance of externally bonded FRP-concrete systems.

**Research Significance:** Changes in performance over time in externally bonded FRP retrofits for various levels of moisture exposure will be quantified.

#### 4.2.6 Mechanistic Modeling of Static and Cyclic Fatigue of FRP Composites

**Problem Statement:** Despite their potential perceived benefits, lack of understanding of degradation mechanisms associated with FRP materials is a barrier to their broader utilization. While the general sequence of damage development is well known, models used to represent this damage are most often empirical or semi-empirical, lacking explicit connection to the underlying mechanisms. Moreover, the materials exhibit considerable variability as does the loading environment. As a result of the current lack of understanding, there is a concern that design “knockdown factors” associated with static and cyclic fatigue are inappropriate. These “knockdown factors” are often based upon ad hoc arguments or empirical models. While they are believed to be conservative, their lack of mechanistic basis may lead to an overloaded structure or, in the worst case, a failure.

**Objectives:** To develop an understanding of the underlying mechanisms that lead to damage development in FRP materials.

##### **Scope of Work:**

- Establish damage development in FRP materials. For example, what is the role of fiber-matrix interfacial debonding on the progressive damage development that leads to additional matrix cracking, delamination, and fiber breakage ultimately leading to catastrophic failure including the potential loss of life. Identify the dissipative mechanisms.
- Quantify the connection between static and cyclic fatigue. Is static fatigue (creep rupture) merely a special case of cyclic fatigue, or are the relevant mechanisms different?
- Develop mechanism based (rather than empirical) models to predict residual strength as a function of damage state.
- Examine interaction between moisture/temperature/stress and fatigue damage development to develop synergistic models incorporating material variability. Evaluate the applicability of Arrhenius-type models.
- Use models for material variability and probabilistic descriptions of typical loading environments for expected applications to develop appropriate design knockdown factors.
- Use a model material system to characterize damage development sequence under  $R=0.1$ ,  $R=10$ ,  $R=-1$ , and  $R=1$  (creep rupture) loading conditions as a function of applied stress level, temperature (constant), and humidification (constant).
- Use a model material system to characterize damage development sequence under  $R=0.1$ ,  $R=10$ ,  $R=-1$ , and  $R=1$  (creep rupture) loading conditions as a function of applied (constant) stress level, temperature (cycling), and humidification (cycling).
- Evaluate connection between  $R=0$  and  $R=0.1$  and  $R=10$  damage development. Determine if static fatigue is special case of cyclic fatigue or must be treated separately.
- Conduct molecular mechanics modeling of stress-temperature-humidity effects on damage development.
- Conduct multi-scale modeling to connect molecular- and continuum-scale models.
- Measure local values of residual matrix stiffness by using techniques such as nanoindentation.



- Use non-destructive monitoring of progressive damage, including the use of X-ray computed tomography and digital volume correlation.

#### **Research Significance:**

- Database of material properties as a function of controlled environment for model material system including material variability will be developed.
- Mechanistic understanding of damage development validated by *in-situ* measurements will be developed.
- Computational/analytical tool to develop appropriate design factors for a specific material system (including specific manufacturing techniques, lay-ups, etc.) as a function of expected use environment will be developed.
- Guidance for structural health prognosis will be provided.

### **5. Concluding Remarks**

In order to further the understanding of aging of FRP composites, the goal of this workshop was to assess the state-of-the-art and consider future R&D needs. This goal was well accomplished by bringing together 35 leading researchers, designers, and owners of infrastructure systems to create a forum for presentations and round table discussions through a two-day program. Focus was placed on additional research, development, and implementation schemes to better predict behavior of FRP structures for their long-term serviceability and reliability. As a result, two documents were produced from the workshop: one was the proceedings of the workshop that included all the plenary presentations of invited speakers and the other was the final report that summarized the findings of the workshop and future research directions. The first document was produced before the workshop took place while the second document was the outcome of the workshop. Both the proceedings of the workshop and the final summary report are available at the workshop website: <http://www.statler.wvu.edu/cfc/research/projects/aging.php>.

With workshop participants identifying future research directions, the larger community interested in research and development for highway transportation FRP applications could, as a follow-up to this workshop, develop an interdisciplinary research program to support some or all of the high impact research topics for future funding by federal agencies, such as FHWA, the Department of Energy, or NSF, State and county Departments of Transportation, industry, or other interested stakeholders.

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## Appendix B Working Group Session Attendance

Participant	Affiliation	Group A: FRP Reinforcement	Group B: FRP Shapes	Group C: Test Methods	Group D: Aging Models
Thiru Aravinthan	U Southern Queensland, AU		X		
Rebecca Atadero	Colorado State University	X			
Charles E. Bakis	Pen State University				Chair
Brahim Benmokrane	University Sherbrooke, Canada	Chair			
Michael Blanford	USHUD				
Tim Bradberry	Texas DOT		X		
John Busel	ACMA		X		
Scott Case	Virginia Tech				X
Jian-Guo Dai	HK Polytechnic University	X			
Emmanuel Ferrier	University of Lyon, France	X			
Mariaenrica Frigione	University of Salento, Italy				X
Douglas Gardner	Maine U		X		
Rakesh Gupta	WVU				X
Trey Hamilton	University of Florida	X			
Gangarao Hota	WVU-CFC		X		
Bruce Johnson	Oregon DOT	X			
Venkatesh Kodur	Michigan State U			X	
Ellen Lackey	University of Mississippi			Chair	
Rich Lampo	USACE				
Ray Liang	WVU-CFC			X	
Weiqing Liu	Nanjing Tech Univ., China				
Emily Maurer	Delaware DOT			X	
Masayuki Nakada	Kanazawa Inst Tech, Japan			X	
Mario A. Paredes	Florida DOT				X
Mohamed Pour Ghaz	NC State University			X	
Samit Roy	University of Alabama				X
David Scott	Georgia Tech		Chair		
Constantinos Soutis	University of Manchester, UK			X	
Louis Triandafilou	USDOT-FHWA	X			
PV Vijay	WVU-CFC	X			
Baolin Wan	Marquette University				X
Harry White	New York DOT		X		

Appendix C Workshop Agenda

*International Workshop*  
***Aging of Composites***

National Transportation Safety Board Training Center  
Ashburn, VA

September 25-26, 2013

Sponsored By

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U.S. Department  
of Transportation

**Federal Highway  
Administration**

Presented By

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 West Virginia University.



## *General Information*

### **Workshop Objectives**

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- 1) Provide a state-of-the-art knowledgebase overview on the aging of composite materials for infrastructure applications.
- 2) Suggest effective methods to collect additional data and procedures to integrate all the information readily available.
- 3) Focus on FRP composite coupon and component resistance factors based on available data.
- 4) Establish future research, development and evaluation roadmap dealing with durability issues and design guidelines.

### **Transportation Information**

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Vans will be available to shuttle participants to/from the hotel to the NTSB Training Center each day. The vans will depart from the hotel at 7:30 AM each day and will depart the NTSB for the hotel at 5:15 PM on Sept 25. To facilitate travelers leaving on Sept 26, one van will depart the NTSB and go directly to Dulles International Airport at 4:30 PM. The remaining vans will depart at the same time going to the Hilton Garden Inn Dulles North.

Participants who miss the shuttles will have to secure their own transportation.

### **Steering Committee**

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Gangarao Hota, West Virginia University: Co-Chair  
Louis Triandafilou, Federal Highway Administration: Co-Chair  
Ruifeng (Ray) Liang, West Virginia University  
Charles Bakis, Penn State University  
Donald Williams, West Virginia Department of Transportation  
Mario Paredes, Florida Department of Transportation  
Mark Skidmore, West Virginia University

### **Travel Reimbursement**

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Mark Skidmore from West Virginia University will be preparing the travel reimbursement forms during the workshop for your approval and signatures. Please see him at the registration table to submit your original receipts for reimbursement. Reimbursement checks should be sent in 6 to 12 weeks.

### **Acknowledgements**

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The Steering Committee and the West Virginia University Constructed Facilities Center are grateful to the Federal Highway Administration through the National Science Foundation for providing the funding for the workshop. We also want to thank all the participants for taking the time out of their busy schedules to participate in this workshop.



## Schedule at a Glance

### 24<sup>th</sup> September 2013

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*Hilton Garden Inn Dulles North*  
22400 Flagstaff Plaza, Ashburn, VA 20148

6:00-8:00 pm Registration  
6:00-8:00 pm Welcome Dinner (Hilton Garden Inn)

### 25<sup>th</sup> September 2013

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*National Transportation Safety Board (NTSB) Training Center*  
45065 Riverside Parkway, Ashburn, VA 20147

6:30 – 7:30 am Breakfast at Hotel (included in Room Charges)  
7:30 – 7:45 am Shuttle Departure to NTSB  
7:45 – 8:00 am Late Registration  
8:00 – 8:20 am Opening Remarks

- Introduction: **Louis Triandafilou**
- Welcome Speech: **Jorge E. Pagán-Ortiz**, Director of the Office of Infrastructure Research & Development, USDOT- Federal Highway Administration
- Workshop Objective and Scope: **Gangarao Hota**

8:20 – 9:20 am GROUP A: Plenary Presentations (page 4) – Chair **Brahim Benmokrane**  
9:20 – 10:20 am GROUP B: Plenary Presentations (page 5) – Chair **David Scott**  
10:20 – 10:30 am Break  
10:30 – 11:30 am GROUP C: Plenary Presentations (page 6) – Chair **Ellen Lackey**  
11:30 – 12:20 am GROUP D: Plenary Presentations (page 7) – Chair **Charles E. Bakis**  
12:20 – 1:15 pm Lunch  
1:15 – 3:00 pm Parallel Group Discussions: Examine the Topic (page 8)  
3:00 – 3:15 pm Break  
3:15 – 5:00 pm Parallel Group Discussions: Examine the Topic Continued  
5:15 pm Shuttle Pick up to Hilton Garden Inn  
6:00 pm Dinner (Hilton Garden Inn)

### 26<sup>th</sup> September 2013

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*National Transportation Safety Board Training Center*

6:30 – 7:30 am Breakfast at Hotel (included in Room Charges)  
7:30 – 7:45 am Shuttle Departure to NTSB  
8:00 – 10:00 am Plenary Summaries (page 8) –Groups A and B Chairs  
10:00 – 10:15 am Break  
10:15 – 12:00 am Plenary Summaries (page 8) –Groups C and D Chairs  
12:00 – 12:45 pm Lunch  
12:45 – 1:30 pm Plenary Discussions: Prioritizing the Needs from All Groups (page 8) – **Gangarao Hota**  
1:30 – 3:00 pm Parallel Group Discussions: RFP Development (page 8) – Group Chairs  
3:00 – 3:15 pm Break  
3:15 – 4:00 pm Plenary Discussions: RFPs (page 8) – **Gangarao Hota**  
4:00 – 4:30 pm Summary of Action Items and Closing Remarks – **Louis Triandafilou**  
4:30 pm Shuttle Pick up to Dulles International Airport and to Hilton Garden Inn Dulles North





## Group A: FRP Internal and External Reinforcements

*Chair: Brahim Benmokrane*

### Topic Areas

- Long term performance data including surface and bond degradation under:
  - Environmental factors (pH, temperature, moisture, freeze-thaw, UV, others)
  - Load types - static, fatigue, creep, thermal and fire
  - Process parameters (cure rate, voids, fiber wrinkling, etc.) and in-service variables (temperature, humidity, wet/dry surface, etc.)
- Design specifications
  - Knock down factors, stress concentration, void effects, manufacturing defects
- Future research
  - Mechanisms of deterioration (strength, stiffness, durability) at micro, meso, macro levels
  - Fabrication and erection
  - Benefit –cost analyses
  - others

### Plenary Presentations: September 25, 2013

8:20	Moisture Conditioning of Bonded FRP Composites	Trey Hamilton
8:30	Field Performance of FRP Repair Materials: The Need for More Data	Rebecca Atadero
8:40	Durability Issues of FRPs for Civil Infrastructure	Brahim Benmokrane
8:50	Aging of Composites of External Bonded CFRP for RC Structures Strengthening	Emmanuel Ferrier
9:00	Durability Issues of Concrete Structures Strengthened with Externally Bonded FRP (EB-FRP) Composites	Jian-Guo Dai
9:10	Oregon DOT Experience with FRP	Bruce Johnson

### Group Members

Brahim Benmokrane (chair)	University of Sherbrooke	Sherbrooke, Canada
Rebecca Atadero	Colorado State University	Fort Collins, CO, USA
Jian-Guo Dai	Hong Kong Polytechnic University	Hong Kong, China
Emmanuel Ferrier	University of Lyon	Lyon, France
Trey Hamilton	University of Florida	Gainesville, FL, USA
Bruce Johnson	Oregon Department of Transportation	Salem, OR, USA
Louis Triandafilou	Federal Highway Administration	Washington, DC, USA
PV Vijay	West Virginia University	Morgantown, WV, USA







## Group B: FRP Shapes

*Chair: David Scott*

### Topic Areas

- Long term performance including joints under varying environments
  - Environmental factors (pH, temperature, moisture, freeze-thaw, UV, others)
  - Loading types – static, fatigue, creep, stress relaxation, shrinkage, fire
  - Process parameters and construction variables including joint design
- Design specifications
  - Knock down factors, stress concentration and stiffening effects
- Future research
  - Mechanisms of deterioration (reduction of strength, stiffness, and durability) at micro, meso, macro levels
  - Fabrication and erection
  - Benefit-cost analyses

### Plenary Presentations: September 25, 2013

9:20	Aging Studies of FRP Composites at WVU-CFC	Gangarao Hota
9:30	Composite Anti-Collision Bumper Systems and Their Durability under Multi-Environmental Factors	Weiqing Liu
9:40	Creep of Pultruded Fiber Reinforced Polymeric Materials in Civil Infrastructure Applications	David Scott
9:50	Aging and Durability Issues of Wood Polymer Composites	Douglas Gardner
10:00	Review of Fiber Composite Structures in Australia	Thiru Aravinthan
10:10	FRP Composites in Texas Infrastructure – How Long Will They Perform?	Tim Bradberry

### Group Members

David Scott (chair)	Georgia Institute of Technology	Atlanta, GA, USA
Thiru Aravinthan	University of Southern Queensland	Toowoomba, Australia
Michael Blanford	US Department of Housing and Urban Development	Washington, DC, USA
Tim Bradberry	Texas Department of Transportation	Austin, TX, USA
Douglas Gardner	University of Maine	Orono, ME, USA
Gangarao Hota	West Virginia University	Morgantown, WV, USA
Richard Lampo	US Army Corp of Engineers	Champaign, IL, USA
Weiqing Liu	Nanjing University of Tech	Nanjing, China





## Group C: Test Methods

*Chair: Ellen Lackey*

### Topic Areas

- Assessment of current standard test methods (ASTM, ACI, etc.)
  - Coupons, components, systems under static, dynamic, fatigue, creep
  - Thermal and fire, e.g. ASTM D1203
  - Shrinkage, bond, stress concentration (intensity) determination
  - Environmental stress cracking methods (ASTM D1693-Bent Strip)
  - Weathering tests
  - Chemical resistance of GFRPs
- Accelerated testing methodology (ATM) and data collection methods
- Data from natural aging
  - Field data collection of in-service FRP structures
- Nondestructive evaluation (NDE) tools
- Future research
  - Field data collection
  - Others

### Plenary Presentations: September 25, 2013

10:30	Fire Performance of Transportation Structures Incorporating FRP	Venkatesh Kodur
10:40	Advanced Test Methods for Evaluating the Durability Performance of FRP Materials	Mohamed Pour Ghaz
10:50	Determining Characteristic Value of Pultruded Composites Exposed to Environmental Conditioning for Use with the LRFD Standard	Ellen Lackey
11:00	Accelerated Testing Methodology for Long-Term Life Prediction of Polymer Composites	Masayuki Nakada
11:10	Compressive Behavior of Composites: Laboratory-based Accelerated Ageing	Costantinos Soutis
11:20	FDOT's Experience with Material Durability and Its Application to Polymers	Mario Paredes

### Group Members

Ellen Lackey (chair)	University of Mississippi	Oxford, MS, USA
Mohamed Pour Ghaz	North Carolina State University	Raleigh, NC, USA
Venkatesh Kodur	Michigan State University	East Lansing, MI, USA
Ruifeng (Ray) Liang	West Virginia University	Morgantown, WV, USA
Masayuki Nakada	Kanazawa Institute of Technology	Hakusan, Ishikawa, Japan
Mario Paredes	Florida Department of Transportation	Gainesville, FL, USA
Costantinos Soutis	University of Manchester	Manchester, United Kingdom
Harry White	New York Department of Transportation	Albany, NY, USA



## Group D: Degradation and Life Prediction Models

*Chair: Charles Bakis*

### Topic Areas

- Material degradation (mechanistic) models
  - Thermosets (VE, PE, Epoxy, PU, Phenolic) and thermoplastics
- Bond measurements (type of forces to be measured)
  - Nano, micro, milli, meso, and macro
- Molecular level understanding of material aging
  - Physical aging and chemical aging
- Finite element and molecular dynamics modeling
- Life prediction models
  - Remaining life model
  - Fatigue life model
  - Creep, temperature, pH, moisture and other combined models
- Calibration of models
  - Lab and natural aging data
- Future research

### Plenary Presentations: September 25, 2013

11:30	Aging Mechanisms in Polymers and Their Composites: Molecular Level Responses	Rakesh Gupta
11:40	Durability of FRP: The Key Role of Cold-cured Thermosetting Resins	Mariaenrica Frigione
11:50	Variable Amplitude Fatigue Lifetime Predictions for FRP Composites	Scott Case
12:00	Aging and Durability Issues for Fiber Reinforced Polymers	Samit Roy
12:10	A Model to Predict the Degradation of FRP Bonded Concrete Joints in Moist Environment	Baolin Wan

### Group Members

Charles Bakis (chair)	Penn State University	State College, PA, USA
John Busel	American Composites Manufacturers Association	Eastchester, NY, USA
Scott Case	Virginia Polytechnic Institute and State University	Blacksburg, VA, USA
Mariaenrica Frigione	University of Salento	Lecce, Italy
Rakesh Gupta	West Virginia University	Morgantown, WV, USA
Emily Maurer	Delaware Department of Transportation	Dover, DE, USA
Samit Roy	University of Alabama	Tuscaloosa, AL, USA
Baolin Wan	Marquette University	Milwaukee, WI, USA





## *Plenary and Group Discussion Objectives*

### **Parallel Group Discussions: Examine the Topic**

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*Sept 25th 1:15 – 5:00 pm*

- 1) What is the state-of-the-art?
  - a. Based primarily on the presentations from the morning sessions.
  - b. Group should come to a consensus understanding of the topic area in terms of the currently available research.
- 2) What are the barriers for FRP composites to be more fully utilized in infrastructure?
  - a. Identify specific issues that have been referenced as hindering implementation.
  - b. Although widespread issues are of the utmost importance, unique issues should be noted for completeness.
- 3) What research can break down these barriers?
  - a. Considering the gaps in current research, what new studies can be undertaken?
  - b. Do the issues lie in more of the same research (additional case studies)?
  - c. What are the most likely funding sources?
- 4) Where should the priorities lie?
  - a. Which research projects would have the most immediate impact?
  - b. What is the size of the market for each study?

### **Plenary Summaries**

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*Sept 26th 8:00 – 12:00 pm*

Summarize to the whole workshop the discussion from the previous day's parallel discussions. The focus is to educate all on the decisions made by the group and address any misunderstandings, not to debate the group's findings.

### **Plenary Discussion: Prioritizing the Needs from All Groups**

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*Sept 26th 12:45 – 1:30 pm*

Using the information presented in the morning, the whole group will prioritize the research needs for infrastructure composites. The merits of each need can be debated as it is ranked.

### **Parallel Group Discussions: RFP Development**

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*Sept 26th 1:30 – 3:00 pm*

In the individual groups, develop draft one-page RFPs based on the highest priority projects chosen by the full workshop. Include statement of work, estimated costs, timelines, collaborations, etc.

### **Plenary Discussions: RFPs**

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*Sept 26th 3:15 – 4:00 pm*

Present the draft RFPs for feedback from the full workshop

*All items will be summarized for inclusion in the final workshop proceedings published by FHWA.*



## Appendix D Opening Speech by Jorge Pagán-Ortiz

### Opening Remarks for the Workshop on Aging of Composites

**Jorge E. Pagán-Ortiz**  
**Director, FHWA Office of Infrastructure R&D**

**September 25, 2013**

On behalf of the Associate Administrator for RD&T, Michael Trentacoste, I would like to welcome each one of you to the workshop. I also thank each one of you for participating in this workshop.

I would like to thank West Virginia University for setting up this workshop, which is being funded through the FHWA's Exploratory Advance Research program, in partnership with the National Science Foundation and the West Virginia University.

I would also like to recognize the participation of international and domestic researchers, State DOT practitioners, DOD and FHWA staff. Also, I would like to recognize Lou Triandafilou, of my staff and Bridge and Foundation Engineering Team Leader, for his assistance in preparing these welcoming remarks.

I want to share with you a few notes about FHWA's involvement in the conduct of fiber reinforced polymer composite studies. Our R&D program in fiber reinforced polymer composites initiated in the 1980's and continued through the 1990's with studies that focused on the characteristics of fiber reinforced polymers.

#### **FHWA FRP R&D Program of the 1980s & 1990s**

- Deck panels and slab superstructures
- Flexural and shear bonded repairs
- Retrofitting concrete columns in high seismic areas
- Conventional concrete reinforcement
- Prestress concrete reinforcement

Our involvement on FRP composites continued from the 1990's through the 2000's – these studies were more directed into how to incorporate fiber reinforced polymer composites into implementation.

#### **FHWA FRP R&D Program of the 1990s & 2000s**

- Developing AASHTO specifications through NCHRP studies for bonded repairs and deck acceptance criteria
- Inspection of in-service decks
- Maintenance & repair guidelines
- Training for designers and contractors

- Reliable cost and performance information
- Efficient design & construction procedures

With regards to partnering with State DOTs, FHWA has also funded State DOT research studies such as:

- DE's FRP slab bridges, pier column & cap wrapping
- VA's FRP beams and truck weigh scale ramp
- MI's load-testing prototype double-T beams w/FRP prestress
- NC's collaborating w/Japan to develop CFRP plates for steel strengthening

West Virginia University has also led studies on fiber reinforced polymer composites such as:

- Environmental effects
- Long-term durability of FRP bars
- Optimal cross-section shapes
- Fatigue behavior of FRP decks
- Shear, creep & ductility of FRP-reinforced beams

Through the FHWA Innovative Bridge Research and Construction (IBRC)/Innovative Bridge Research and Deployment (IBRD) programs, studies have been funded on:

- Decks and slabs
- Bonded repairs
- Reinforcing & grids
- Prestressing
- Glulam-reinforced
- Beams
- Deck drainage inlets

FHWA continues support of FRP implementation through the goals established for this workshop:

- 1) Provide state-of-the-knowledge base overview of current understanding on aging
- 2) Establish future R&D roadmap on aging behavior of FRP composites for infrastructure.

As a matter of fact, these goals have a direct link to the current FHWA TFHRC Strategic Plan-Bridges & Structures R&D:

- Develops recommended guidelines and specifications for design, construction, testing, evaluation and preservation
- Advanced materials & systems

The workshop's goals are also linked to the U.S. DOT Goal of State of Good Repair:

- Maintain safe & efficient operating conditions on nation's transportation system through data-driven and performance-based infrastructure investments

Your active participation throughout this workshop will be very important as we will be addressing the lack of understanding on durability and life-cycle performance, which have been major technical obstacles for safe & economical field implementation of FRP composites.

Important areas to be covered include:

- Durability
- Environmental considerations
- Loading considerations
- Physical aging
- Chemical aging
- Data from accelerated test methodology
- Data from natural aging
- Modeling
- Life prediction models
- Design recommendations

I wish all of you a very successful workshop.