Proceedings of the
International Workshop on

Aging of FRP Composites

National Transportation Safety Board Training Center
Ashburn, VA

September 25-26, 2013
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Sponsored By

U.S. Department of Transportation
Federal Highway Administration

Presented By

NSF

CFC Constructed Facilities Center

Center for Integration of Composites into Infrastructure

West Virginia University

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General Information

Workshop Objectives

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

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

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

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

The Steering Committee and the West Virginia University Constructed Facilities Center are grateful to Exploratory Advanced Research (EAR) Program of the U.S. Department of Transportation – Federal Highway Administration (USDOT-FHWA) 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

24th September 2013

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)

25th September 2013

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)

26th September 2013

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	Costastantinos 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
Costastantinos 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

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

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

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

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

Sept 26th 3:15 – 4:00 pm

Present the draft RFPs for feedback from the full workshop

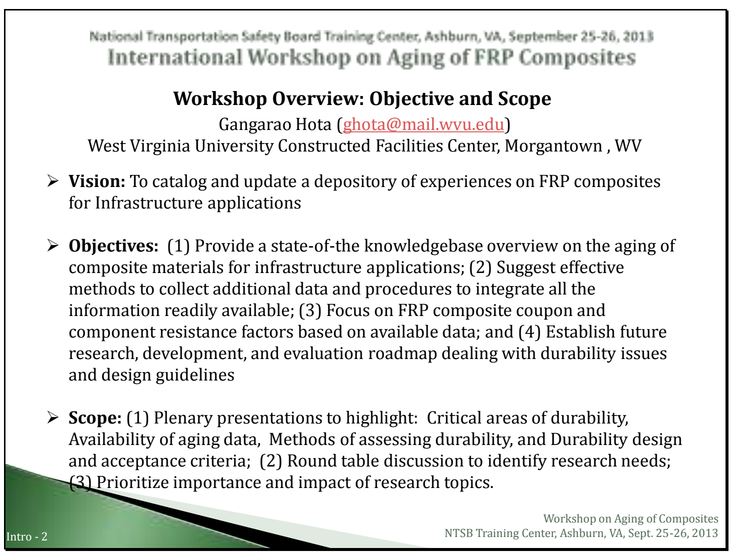
All items will be summarized for inclusion in the final workshop proceedings published by FHWA.

Workshop Overview: Objective and Scope

Gangarao Hota (ghota@mail.wvu.edu)
West Virginia University Constructed Facilities Center, Morgantown , WV

Workshop Overview - Slide 1

Workshop Overview - Slide 2



Workshop Overview - Slide 3

FRP Composites

- Composite structural shapes, components and systems
- Re-bar, wraps and strips for strengthening or reinforcement of members
- Composites paired with conventional materials - hybrids

Mass-Manufacturing Techniques

- Filament Winding
- Compression Molding
- VARTM
- Pultrusion
- Injection Molding (only for Thermoplastics)

High-Volume Applications

- Transportation/Highway Infrastructure Systems
- Waterfront Structures including underwater piers and bents
- Buildings – office, maintenance, storage
- Poles and Pipes
- Chemical Treatment Plants, Mining Applications, Off-shore Systems

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Workshop on Aging of Composites
NTSB Training Center, Ashburn, VA, Sept. 25-26, 2013

Workshop Overview - Slide 4

Aging Mechanisms (fibers, polymers & interface)

- Thermal and Fire (chemical & physical process at room & elevated temperatures)
- Weathering (photo-oxidation, water immersions, pollution effects, erosion)
- Chemical
- Environmental Stress Cracking (chemical compatibility, liquid diffusion, micro-voids, craze cracks, stress concentration)
- Creep and Fatigue
- Others (e.g. bio-degradation of certain polymers, fungi attacks)
- Cumulative damage (e.g. stress- temperature –pH)

Intro - 4

Workshop on Aging of Composites
NTSB Training Center, Ashburn, VA, Sept. 25-26, 2013

Workshop Overview - Slide 5

Viscoelastic Behavior of FRPs

Current Understanding:

- Focus on linear viscoelastic behavior since bi-directional composites with continuous fibers and fabrics behave mostly linearly.
- Findley's Power Law and other models
- Mechanical behavior of composite materials and components; not systems.

Need:

- Better understanding of molecular & micro scale arrangements to establish load – deformation behavior
- Mechanical & aging studies are needed to develop constitutive relations; failure models under multi-axial stress including residual stresses
- Interaction of damage modes & their effects on strength and durability
- Improved models to predict crack tip behavior?

Intro - 5

Workshop on Aging of Composites
NTSB Training Center, Ashburn, VA, Sept. 25-26, 2013

Definition: Creep, creep rupture, stress relaxation, time-dependent deformation recovery, frequency-dependent fatigue life

Workshop Overview - Slide 6

Areas of Focus and Discussion Topics

Group A: FRP Internal and External Reinforcement (Rebar, Wraps, Strips)

- 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

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Workshop on Aging of Composites
NTSB Training Center, Ashburn, VA, Sept. 25-26, 2013

Workshop Overview - Slide 7

Group B: FRP Shapes (deck, beams, columns, fender-piles, etc.)

- 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

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Workshop on Aging of Composites
NTSB Training Center, Ashburn, VA, Sept. 25-26, 2013

Workshop Overview - Slide 8

Group C: Test Methods

- 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

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Workshop on Aging of Composites
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Workshop Overview - Slide 9

Group D: Material Degradation and Life Prediction Models

- 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

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Workshop on Aging of Composites
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Workshop Overview - Slide 10

Working Groups *

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		X		
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		X		
Ray Liang	WVU-CFC			X	
Weiqing Liu	Nanjing U of Tech, China		X		
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 N Triandafilou	USDOT-FHWA	X			
PV Vijay	WVU-CFC	X			
Baolin Wan	Marquette University				X
Harry White	New York DOT			X	

* Volunteer as group Recorder is needed for each group.

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Group A: FRP Internal and External Reinforcements

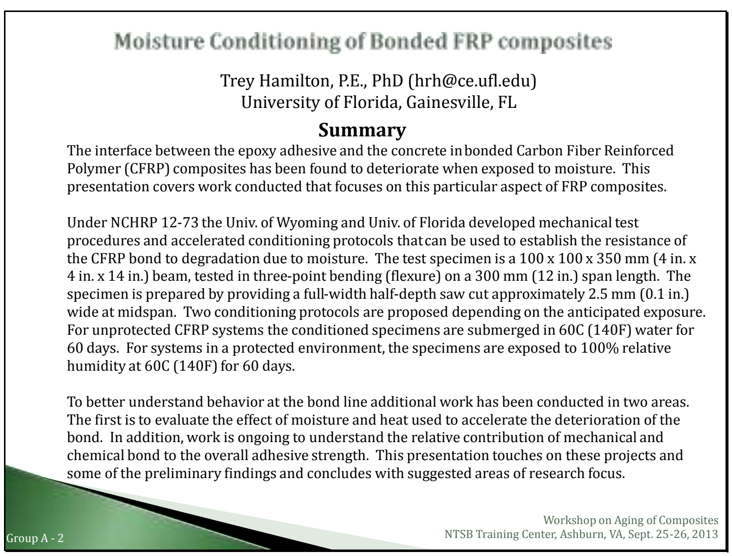
Chair: Brahim Benmokrane

Moisture Conditioning of Bonded FRP Composites

Trey Hamilton, P.E., PhD (hrh@ce.ufl.edu)
University of Florida, Gainesville, FL

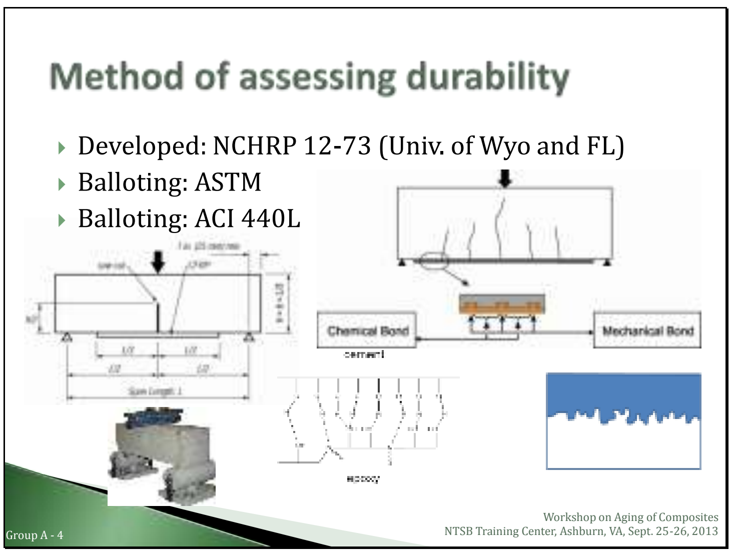
Group A - Slide 1

Group A - Slide 2

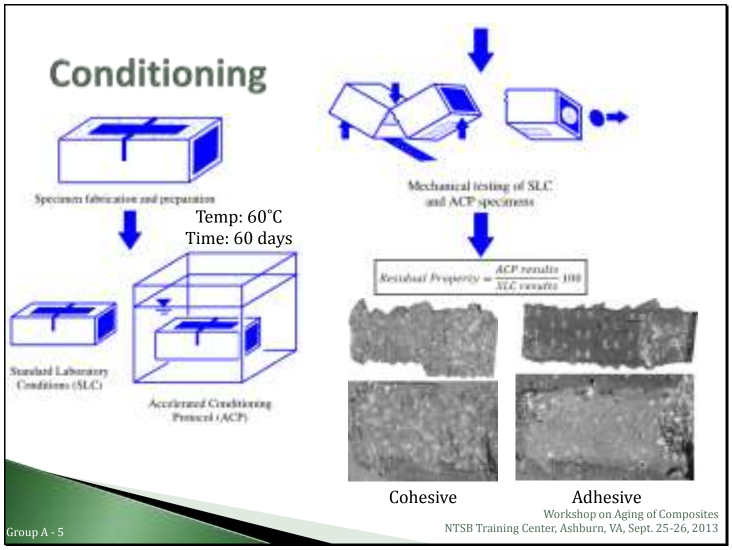


Group A - Slide 3

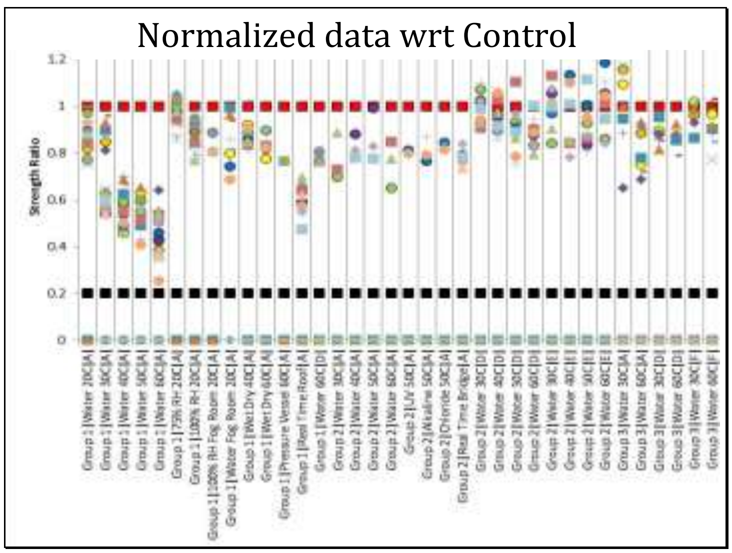
Group A - Slide 4



Group A - Slide 5



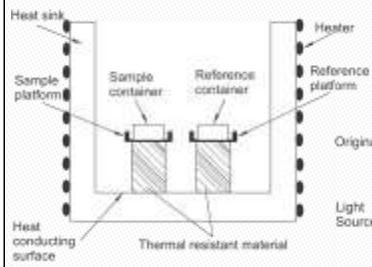
Group A - Slide 6

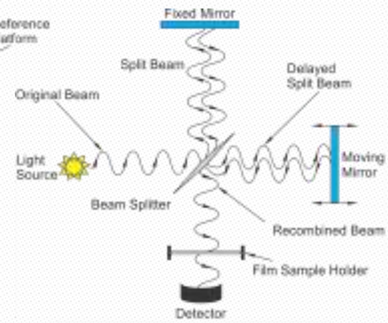


Group A - Slide 7

Epoxy Testing

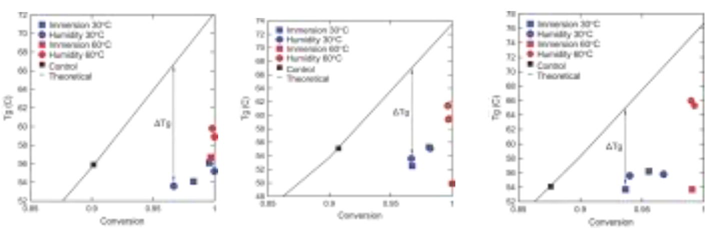
- Differential Scanning Calorimeter (DSC) to find Tg.
- Fourier Transform Infrared Spectrometry (FTIR) to measure water content and conversion.





Group A - Slide 8

Epoxy Testing – Effect of plasticization



- Elevated temperatures increased epoxy conversion (improving Tg).
- Moisture increased epoxy water content (reducing Tg).
- Tg of 30C samples is lower than that of 60C samples under humid conditions

Group A - 8

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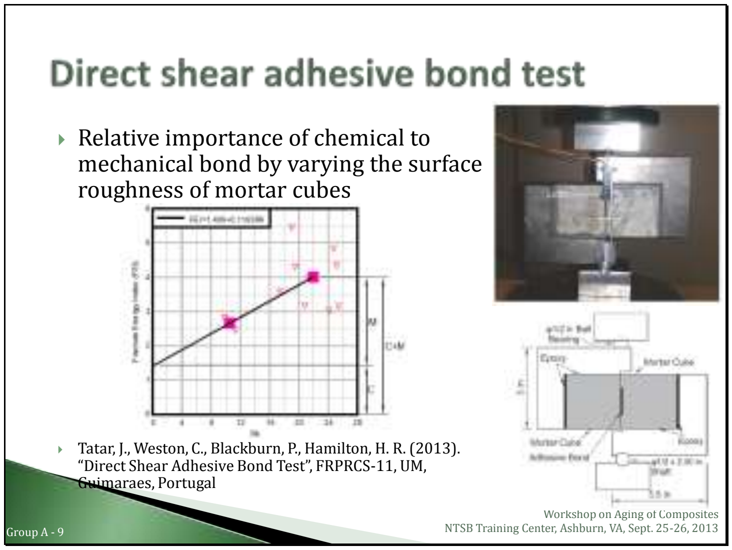
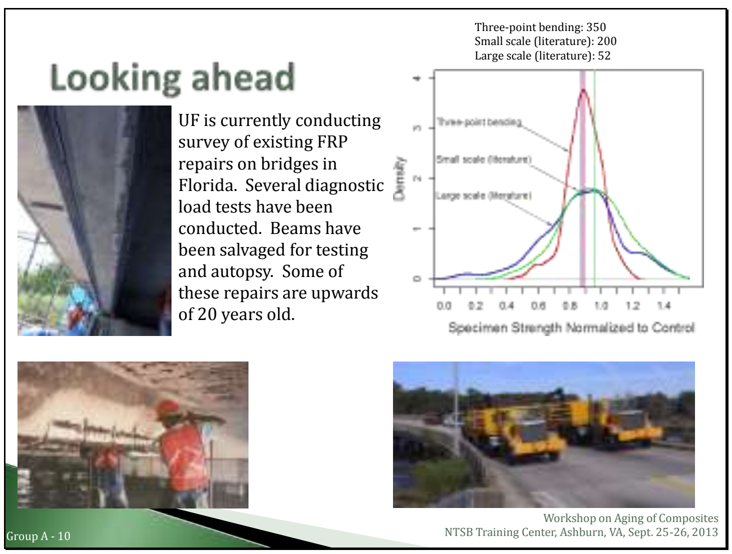
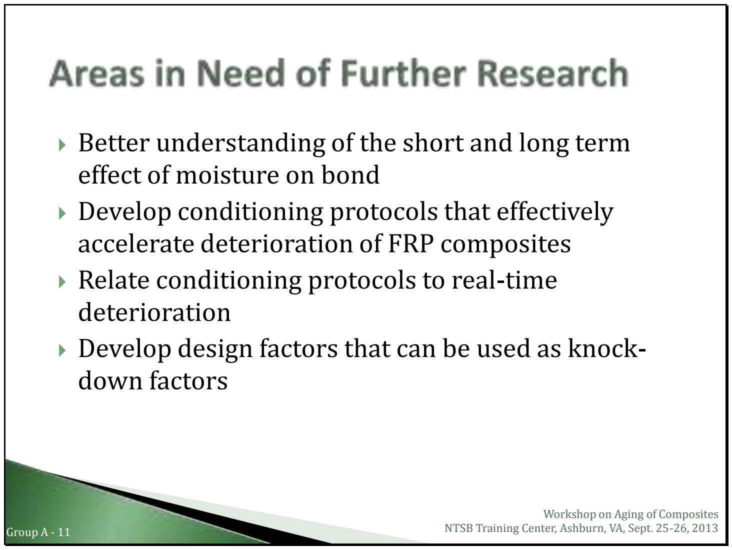
Group A - Slide 9



Group A - Slide 10



Group A - Slide 11



Field Performance of FRP Repair Materials: The Need for More Data

Rebecca Atadero(ratadero@engr.colostate.edu)
Colorado State University, Fort Collins, CO, 80523

Group A - Slide 12

Group A - Slide 13

Field Performance of FRP Repair Materials: The Need for More Data

Rebecca Atadero(ratadero@engr.colostate.edu)
Colorado State University, Fort Collins, CO, 80523

Summary

An important area for further research is the performance of externally bonded FRP materials in the field. FRP has been applied as a repair material on numerous structures over the last twenty years, yet very little information on the performance of these applications is available. The synergistic processes affecting FRP properties in the field including field application/curing, loading, and highly variable environmental conditions cannot be fully simulated in the laboratory.

A recent study conducted for the Colorado Department of Transportation considered the performance of externally bonded CFRP applied to the arches of the Castlewood Canyon Bridge which underwent major reconstruction in 2003. This study indicated that there was likely some degradation of the repair occurring over time, but was limited by the lack of baseline data. Direct tension pull off tests indicated lower bond strengths and less desirable failure modes. Significant areas showed debonding, and debonded regions identified during previous routine bridge inspections had grown significantly. Many tensile coupons had strengths below manufacturer design values. Further work at additional sites is needed to build on these findings.

This study illuminated several challenges that must be considered in future durability studies. Currently the techniques available for inspection are limited and bridge inspectors may have little experience with FRP. Baseline data is vital and should be carefully collected and maintained. Recording spatial and temporal data on debonding can be very time consuming.

Group A - 13

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Group A - Slide 14

Castlewood Canyon Bridge

- Built: 1946
- Major reconstruction: 2003
- Field evaluation of CFRP: 2011

Prior to repair the structure suffered from severe corrosion and spalling.

CFRP was applied longitudinally on the underside of the arch for flexure. The entire arch was then wrapped laterally, leaving some vents on the underside.

Photos by Mansour Mohseni, CDOT

Group A - 14

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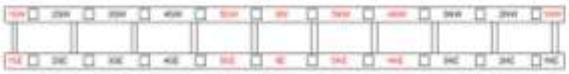
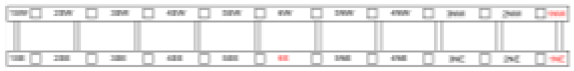
Group A - Slide 15

Direct Tension Pull-off Tests

- Testing conducted in 2003 as part of quality control efforts (locations indicated in red) – 42 total



- Testing conducted in 2011 as part of field evaluation (locations indicated in red) – 27 total



- Access was difficult in 2011

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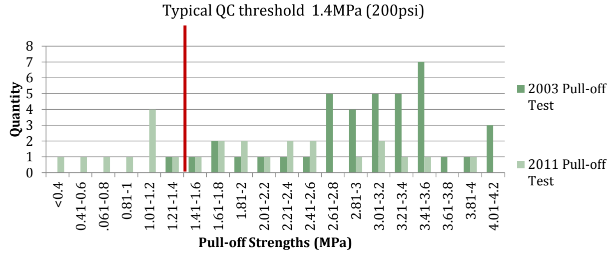
Direct Tension Pull-off Test Results

Histogram of Pull-Off Strengths



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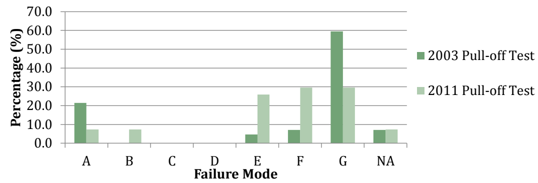
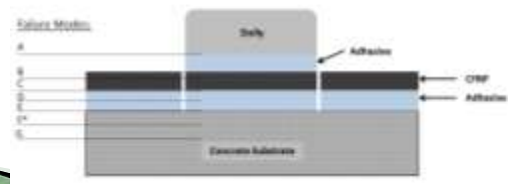
Direct Tension Pull-off Test Results

Change in Failure Mode –ASTM D7522





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Direct Tension Pull-off Test Specimens

- Many of the weak pull-off tests showed thick layers of a white filler material between the FRP and concrete.
- Does the filler have an effect on bond strength, or the potential for debonding?

Layer of white filler at the bond failure surface.

Filler thickness varied over the arch. These are samples removed for tension tests at two different locations.

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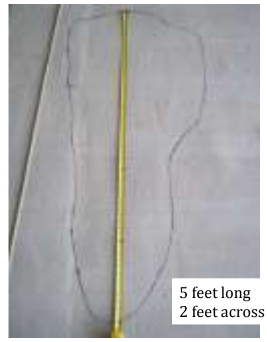
Debonding

- Thermal imaging and tap tests were conducted across the entire upper surface of the east arch.
- Areas that had been identified in previous field assessments had grown in size.
- Many apparently new debonded regions were found – some quite large.

2011 size: roughly 14"x14"

The debonded regions in these two figures were found in the same bay of the bridge, suggesting the large region shown at the right developed in a comparatively short period of time (since 2007).



5 feet long
2 feet across

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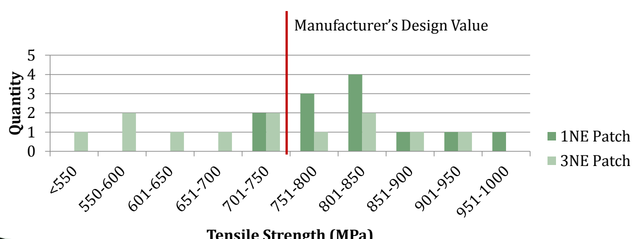
Tension Tests

- Two debonded regions were removed from the bridge and cut into tensile coupons.



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Limitations

- At the time of the repair, no consideration was given to future study of the FRP durability.
- Baseline values for the material as applied to the bridge could not be determined for the FRP tensile strength and modulus.
- The only intermediate evaluations were routine bridge inspections.
- The difficulty of access to the bridge limited the scope of this evaluation.

Conclusions

- There was likely some deterioration of the CFRP and its bond to the concrete.
- We are not able to quantify the amount of deterioration due to a lack of baseline values.
- Similar studies need to be conducted at other repair sites to understand typical field performance.
- Planning and design of repairs should consider the future desire for durability data by carefully collecting, documenting and maintaining baseline values and providing sacrificial areas so that the FRP can be tested without damaging the repair.

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Topics in Need of Further Research

- Simple and accurate techniques for field assessment of externally bonded FRP are needed for researchers and bridge inspectors.
- Effect of filler materials and their thickness on FRP-concrete bond performance.
- Correlation between debonding and growth of debonded areas with environmental and loading conditions.
- Effectiveness of filling debonded areas with epoxy injection.
- Ways to easily assess the impact of debonding on the performance of the repaired structure.
- Means of effective documentation (both spatial and temporal).
  - Areas of shotcrete placement
  - Locations where voids detected during QC inspection were filled with epoxy injection
  - Size and shape of debonded regions over time

The research described herein was funded by the Colorado Department of Transportation and the Mountain Plains Consortium (Region 8 UTC).

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Durability Issues of FRP for Civil Infrastructure

Professor Brahim Benmokrane, FACI, FCSCE, FIIFC, FCAE, FEIC
(Brahim.Benmokrane@USherbrooke.ca)

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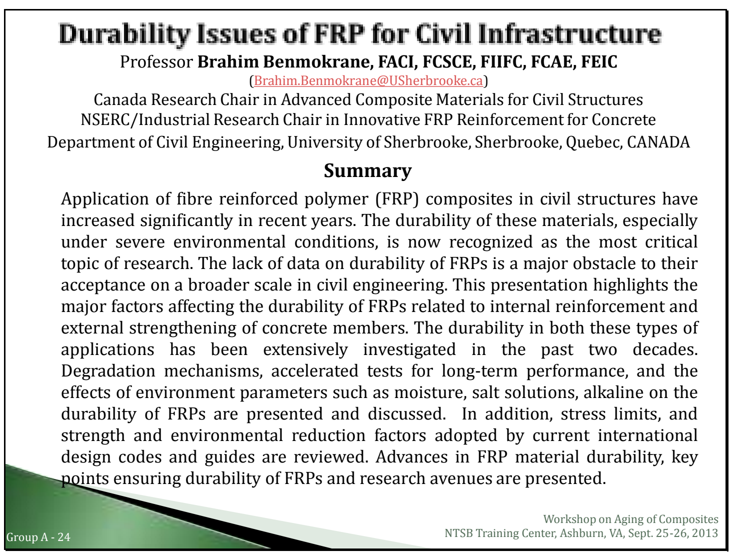

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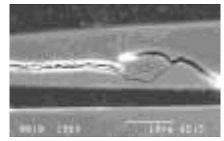
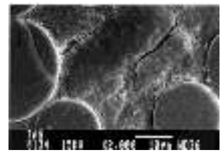
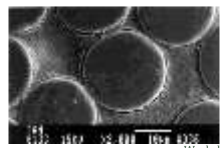
Factors Affecting the Durability of FRPs

Degradation processes in FRPs are typically denoted as:

1. Fiber dominated
2. Matrix dominated, or
3. Interface dominated

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Factors Affecting the Durability of FRPs

It is important to understand that the durability performance of the FRP materials (micro sized fibers in polymer matrices) is intrinsically controlled by the microstructure, which is in turn controlled by:

- the choice of the constituent materials
- the interface (interphase) development
- and the manufacturing process

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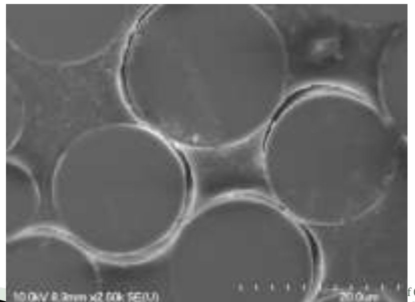
Is bonding at the interface durable?

- The tensile strength of this particular basalt FRP bar sample conditioned in alkaline solution at 60°C during 3 months has been reduced by more than 45% because load transfer has been highly compromised by the development of fiber-matrix debonding



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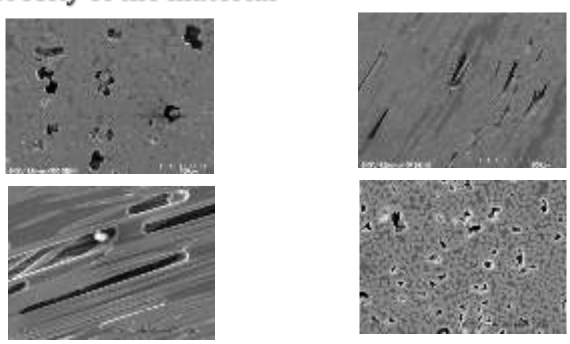
Long-term durability may also be affected by the porosity of the material



Air bubbles and poor fiber wetting make the material more porous and therefore more sensitive to moisture and corrosive fluid ingress. Diffusion of water or aqueous solutions along the fibers may weaken the bond strength at the interface.

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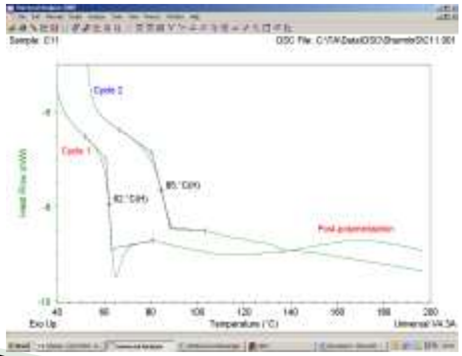
Another Factor Affecting the Long-Term Durability

Glass Transition temperature (Tg)



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Accelerated Aging Tests

1. Assumption is that degradation is caused primarily by a single chemical reaction
2. If assumption is correct, then rate of reaction can be increased by increasing temperature
3. Specimens are ‘aged’ by placing them in solution baths (e.g., water, alkaline, salt) at an elevated temperature

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Accelerated Aging Tests

Alkali Resistance With Sustained Tensile Load

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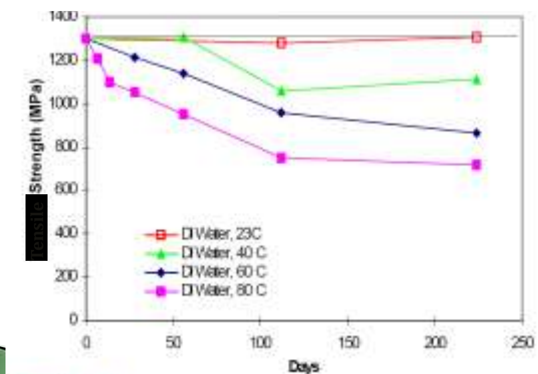
Accelerated Aging Tests

Strength loss = f (time, temperature)



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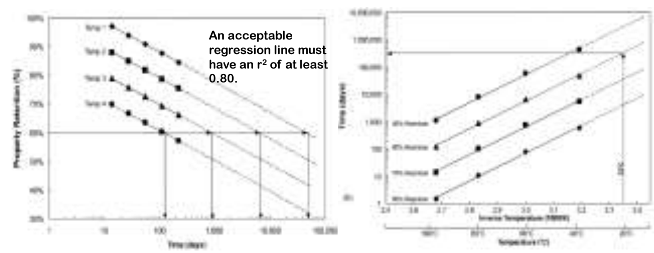
Prediction of Long-Term Strength

Construction of Arrhenius Plot

1st approach: Time may be plotted as a function of inverse absolute temperature for various percentages of property retention.



(a) Plot of property retention as a function of time

(b) Arrhenius plot for service life as a function of temperature and percent retention

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First Field Study (2004)

DURABILITY STUDY ON CONCRETE CORES

To determine the effect of ageing in the field after several years in service, concrete cores containing GFRP bars/grids have been extracted from five Canadian bridges and analyzed

1. Joffre Bridge, QC (ribbed-deformed GFRP Bars)
2. Crowchild Bridge, AB (ribbed-deformed GFRP Bars)
3. Hall's Harbour, NS (sand-coated GFRP Bars)
4. Waterloo Creek, BC (GFRP Grid)
5. Chatham, ON (GFRP Grid)

SPECIFIC: Microscopic and physico-chemical analysis on core samples.

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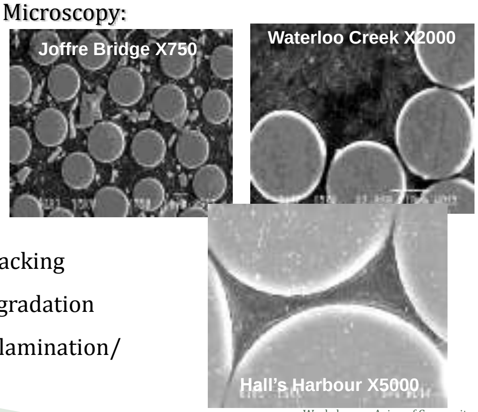
First Field Study (2004) - RESULTS (Cont…)

Scanning Electronic Microscopy:



- No resin microcracking
- No glass fibre degradation
- No significant delamination/ debonding

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Conclusion from First Field Study

- 5 to 8 years of service condition
- No Evidence of debonding between GFRP and concrete
- Alkali attack could not be detected in the GFRP reinforcement materials.
- No deterioration of GFRP reinforcement took place in any of the field demonstration structures.
- The results of this study were the basis for the version of the Canadian Highway Bridge Design Code (CSA S6-06) allowing the use of GFRP as primary reinforcement and prestressing tendons in concrete components provided the stress levelin GFRP at SLS does not exceed 25% of its ultimate strength.

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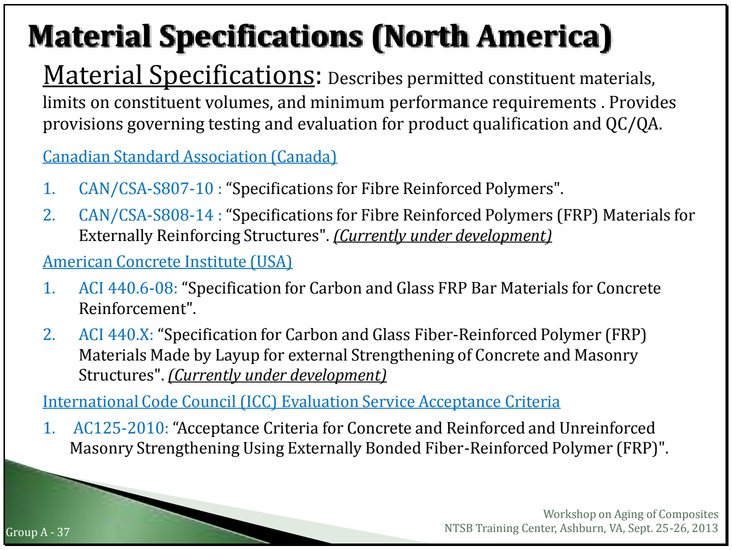

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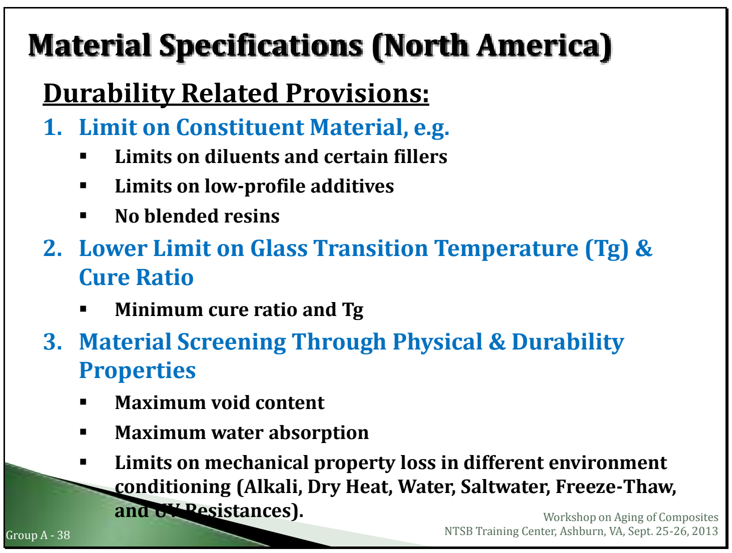

First published in 1999, the ACI 440.1R-06 evolved from emerging technology to ACI standard publications on the use of FRP bars to reinforce concrete. This publication has gone through 3 iterations over the years to refine the design equations used in this document. This has become a well reference and used world-wide design document as the authority for internally reinforced concrete with FRP bars.

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Concluding Remarks

Corrosion resistance is without doubt the main motive and attraction to use FRPs over the steel
Modes of degradation of FRPs (in civil engineering) are well understood
Test methods and requirements for assessing FRPs with high durability have been proposed
Application of FRP's in different civil infrastructures has been proved to be very successful to date
Glass FRP bars are durable in concrete
The durability performance of FRP materials is generally very good in comparison with other, more conventional, construction materials
Basalt FRP bars present interface problems. These problems should be resolved before their testing qualification according to the requirements of Material Specifications and Standards (such as CAN/CSA S807 and ACI 440.6) and implementation in field pilot projects.

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Research avenues

- Synergistic (combined) Effects of Load, Moisture, and Temperature on the Thermo-mechanical Properties of FRPs (e.g., Reinforcing Bars, Prestressing Tendons, Bonded FRP Systems).
- Development of Accelerated Ageing Testing Protocols Simulating the Field Conditions (ACI 440L Sub-Committee is preparing a guide on this topic). Development and/or enhancement of predictive models.
- 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)
- Enhancement of Performance of FRPs Using New Materials (Nanocomposites & Nanomaterials)
- 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. Life predictive models and development of accurate life cycle assessment of FRPs. Reliable resistance factors.

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Aging of Composites of External Bonded CFRP for RC Structures Strengthening

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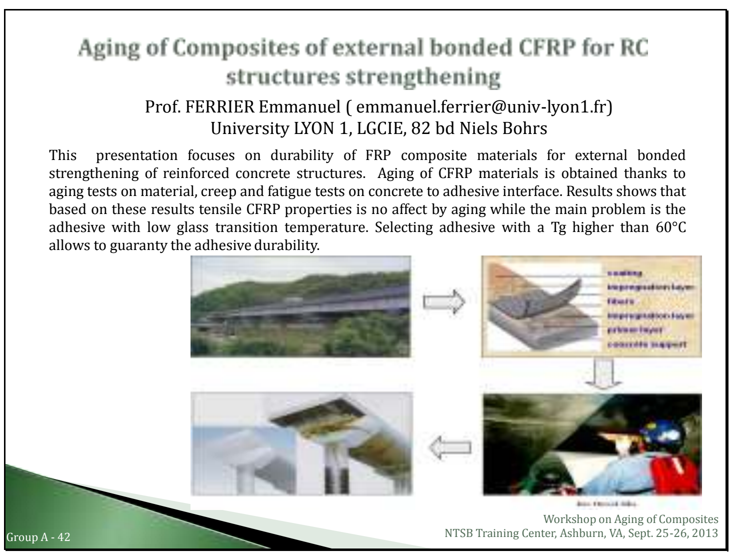

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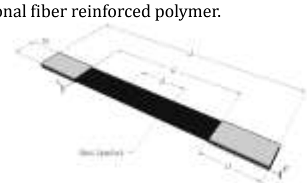
Methods of Assessing Durability Issues of FRPs

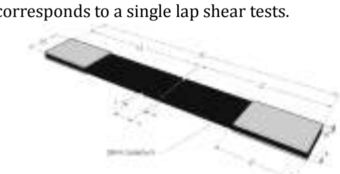
1. Aging on CFRP laminate, and FRP/FRP interface using single lap shear test

The tensile tests have been done with the European norm NF EN ISO 527-5 used for unidirectional fiber reinforced polymer.



Designation	Size [mm]
L_3	250
L_2	150
b_1	15
L_0	50
h	1,2
L_T	50
h_T	1

The interlaminar shear strength is obtained by ASTM D 3165 standard. The test principle corresponds to a single lap shear tests.



Designation	Size [mm]
L_0	190
L_1	101.3
L_2	86.2
L	12.7
h	2 x 1.2
b_1	25
c	2.5
h_T	1
L_T	40

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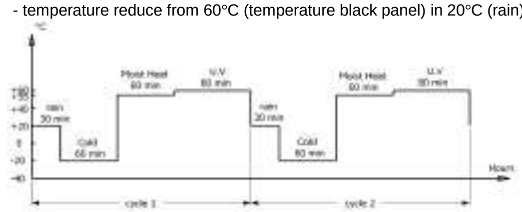
Methods of Assessing Durability Issues of FRPs

1. Aging on CFRP laminate, and FRP/FRP interface using single lap shear test

The ageing is done with an apparatus in a unique room and regulated by a program, in accordance with the section 6.1 of French norm NF T 30-049. Notably in relation to thermal shocks between stages like describe below:

- temperature going to 20°C (rain) to minus 20°C (frost) in less than 10 min,
- taken back up in temperature from - 20°C (frost) in 55°C (humid warmth) in 30 min ±10 min,
- taken back up in temperature of 55°C (humid warmth) in 60°C (temperature black panel) in 5 min ±2 min,
- temperature reduce from 60°C (temperature black panel) in 20°C (rain) in 5 min ±2 min.



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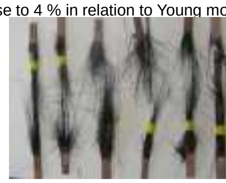
Aging Data Available

1. Aging on CFRP laminate, and FRP/FRP interface using single lap shear test

Tensile tests

Tests show that the ageing cycles does not have influence on general behaviour in tension of CFRP laminates. In effect, the difference between results before and after aging is close to 1 % for the strength; it is close to 4 % in relation to Young modulus.



	f_f [MPa]	E_f [MPa]
Sample before aging	3195	179781
Sample after aging	3158	172000
Comparison	**× 0,988**	**× 0,957**

Interlaminar shear test

Interlaminare tests show that the effect of ageing is rather favourable to the system of strengthening. In effect, average shear strength after ageing increased by 21 % when tests samples were subjected to the 100 cycles of ageing.

	τ_{moy} [MPa]
Sample before aging	11.69
Sample after aging	14.15
Comparison	**× 1.21**

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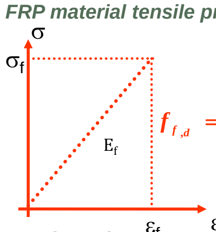
Sample Design Recommendations : French standart

FRP material tensile properties



$$f_{f,d} = \frac{\alpha_f f_f}{\gamma_f}$$

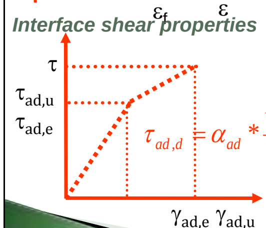
SLS γ_f = 1,4
ULS γ_f = 1,25 → Carbon epoxy laminate

SLS γ_f = 2
ULS γ_f = 1,4 → Carbon epoxy applied with hand lay up

SLS γ_f = 2,5
ULS γ_f = 1,6 → Glass epoxy applied with hand lay up

For instantaneous behaviour : α_f = 1
For long term purpose : α_f = 0,65

Interface shear properties



$$\tau_{ad,d} = \alpha_{ad} * \frac{\tau_{ad,e}}{\gamma_{ad}}$$

ULS → γ_{ad} = 1,4

SLS → γ_{ad} = 2

α_{ad} = 0,8 if TG > 50°C
(TG : Glass transition temperature

α_{ad} = 0,4 if TG < 50°C

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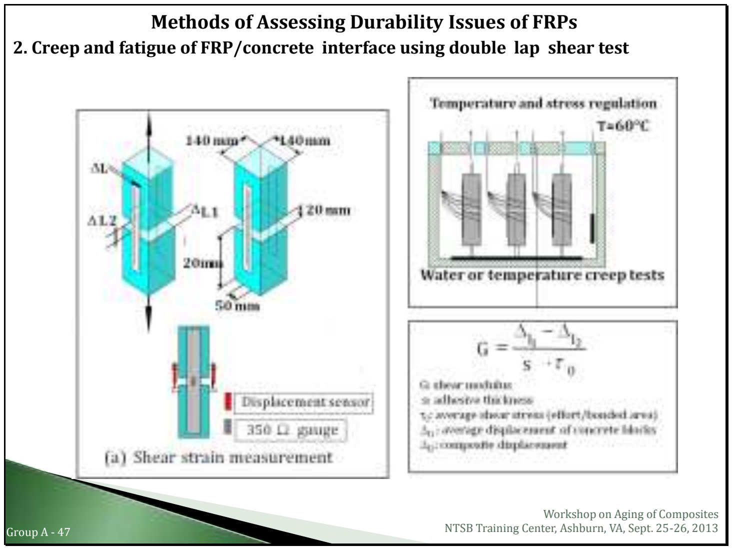

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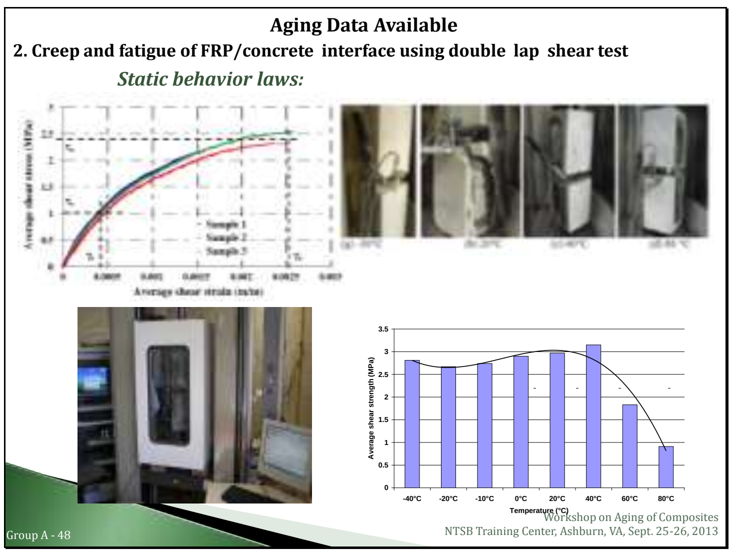

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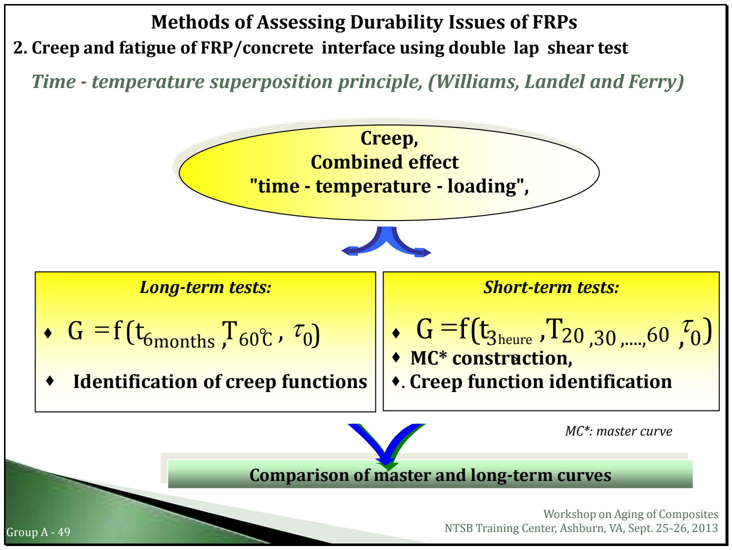

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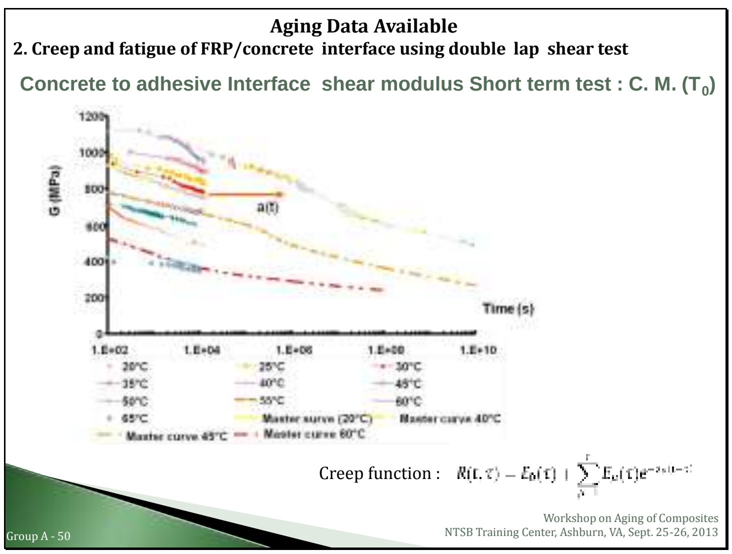

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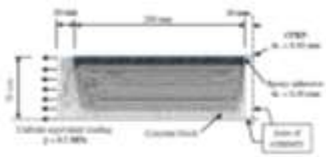
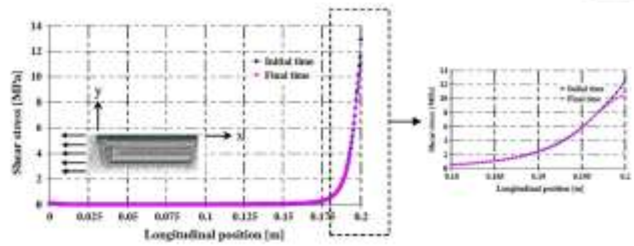
Aging Data Available

Concrete to adhesive Interface: Effect of creep FEM modeling

Stress redistribution from FRP to concrete





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Sample Life Prediction Models

Evaluation of shear stress limit

$$\gamma(t,T) = \gamma_{inst} + \gamma_{creep}$$

$$\gamma(t,T) = \tau_0 \cdot D(t,T)$$

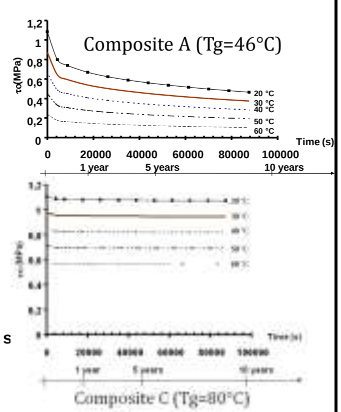
$$\tau_0 = \frac{\gamma(t,T)}{D(t,T)}$$

$$\tau_{adm} = \frac{\gamma_e}{D(t,T)}$$

τ_0 : initial shear stress; D (t,T): creep function

$\gamma(t,T)$: initial shear strain; τ_{adm} : allowable shear s

γ_e : shear strain limit



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Sample Topics in Need of Further Research

- Creep can be benefit for Interface by reducing local peak shear stress, investigation on structures is needed
- Creep depends on adhesive glass transition temperature, higher quality of epoxy is needed
- Fixed the values of safety factors with regards to all obtained data
- Combined effect of stress, temperature, moisture.
- Develop case study analysis already obtained to control the limit of existing standard

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Aging of Composites of external bonded CFRP for RC structures strengthening

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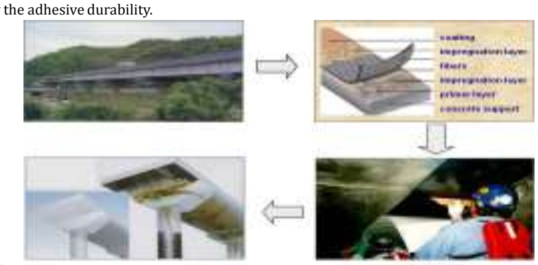
This presentation focuses on durability of FRP composite materials for external bonded strengthening of reinforced concrete structures. Aging of CFRP materials is obtained thanks to aging tests on material, creep and fatigue tests on concrete to adhesive interface. Results shows that based on these results tensile CFRP properties is no affect by aging while the main problem is the adhesive with low glass transition temperature. Selecting adhesive with a Tg higher than 60°C allows to guaranty the adhesive durability.



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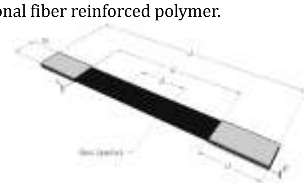
Methods of Assessing Durability Issues of FRPs

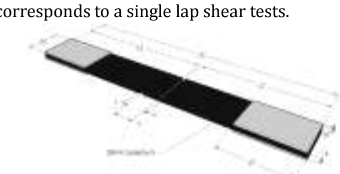
1. Aging on CFRP laminate, and FRP/FRP interface using single lap shear test

The tensile tests have been done with the European norm NF EN ISO 527-5 used for unidirectional fiber reinforced polymer.



Designation	Size [mm]
L_3	250
L_2	150
b_1	15
L_0	50
h	1,2
L_T	50
h_T	1

The interlaminar shear strength is obtained by ASTM D 3165 standard. The test principle corresponds to a single lap shear tests.



Designation	Size [mm]
L_0	190
L_1	101.3
L_2	86.2
L	12.7
h	2 x 1.2
b_1	25
c	2.5
h_T	1
L_T	40

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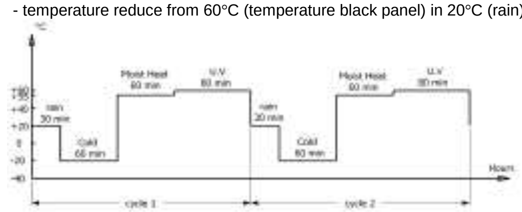
Methods of Assessing Durability Issues of FRPs

1. Aging on CFRP laminate, and FRP/FRP interface using single lap shear test

The ageing is done with an apparatus in a unique room and regulated by a program, in accordance with the section 6.1 of French norm NF T 30-049. Notably in relation to thermal shocks between stages like describe below:

- temperature going to 20°C (rain) to minus 20°C (frost) in less than 10 min,
- taken back up in temperature from - 20°C (frost) in 55°C (humid warmth) in 30 min ±10 min,
- taken back up in temperature of 55°C (humid warmth) in 60°C (temperature black panel) in 5 min ±2 min,
- temperature reduce from 60°C (temperature black panel) in 20°C (rain) in 5 min ±2 min.



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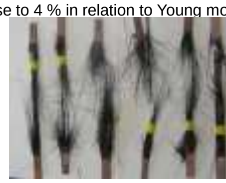
Aging Data Available

1. **Aging on CFRP laminate, and FRP/FRP interface using single lap shear test**

Tensile tests

Tests show that the ageing cycles does not have influence on general behaviour in tension of CFRP laminates. In effect, the difference between results before and after aging is close to 1 % for the strength; it is close to 4 % in relation to Young modulus.



	f_f [MPa]	E_f [MPa]
Sample before aging	3195	179781
Sample after aging	3158	172000
Comparison	**× 0,988**	**× 0,957**

Interlaminar shear test

Interlaminare tests show that the effect of ageing is rather favourable to the system of strengthening. In effect, average shear strength after ageing increased by 21 % when tests samples were subjected to the 100 cycles of ageing.

	τ_{moy} [MPa]
Sample before aging	11.69
Sample after aging	14.15
Comparison	**× 1.21**

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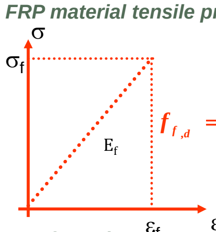
Sample Design Recommendations : French standart

FRP material tensile properties



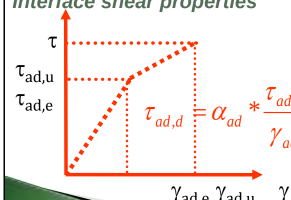
$$f_{f,d} = \frac{\alpha_f f_f}{\gamma_f}$$

SLS γ_f = 1,4
ULS γ_f = 1,25 → Carbon epoxy laminate

SLS γ_f = 2
ULS γ_f = 1,4 → Carbon epoxy applied with hand lay up

SLS γ_f = 2,5
ULS γ_f = 1,6 → Glass epoxy applied with hand lay up

Interface shear properties



$$\tau_{ad,d} = \alpha_{ad} * \frac{\tau_{ad,e}}{\gamma_{ad}}$$

For instantaneous behaviour : α_f = 1
For long term purpose : α_f = 0,65

ULS → γ_{ad} = 1,4

SLS → γ_{ad} = 2

α_{ad} = 0,8 if TG > 50°C
(TG : Glass transition temperature

α_{ad} = 0,4 if TG < 50°C

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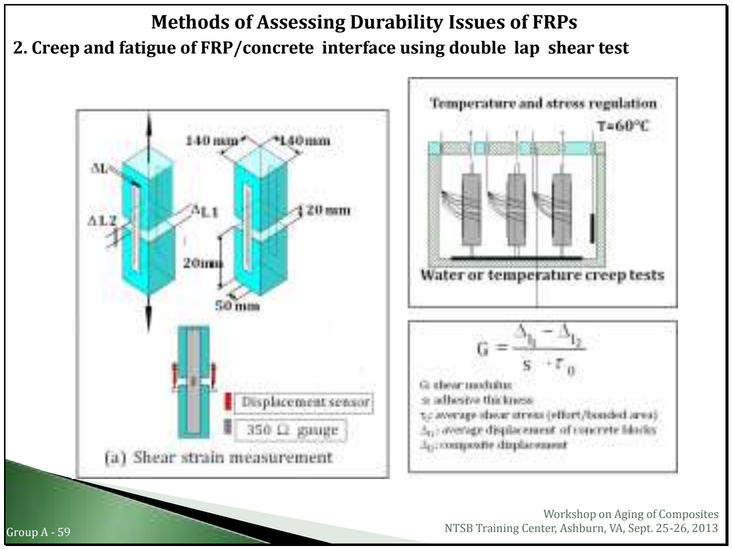

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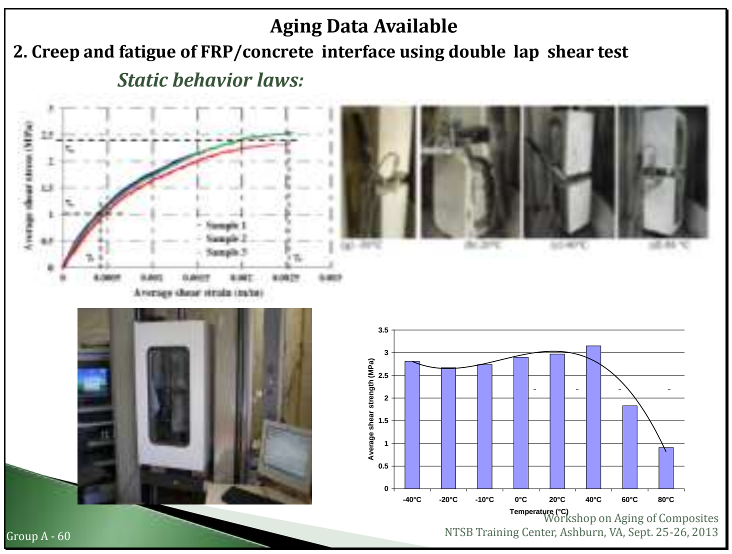

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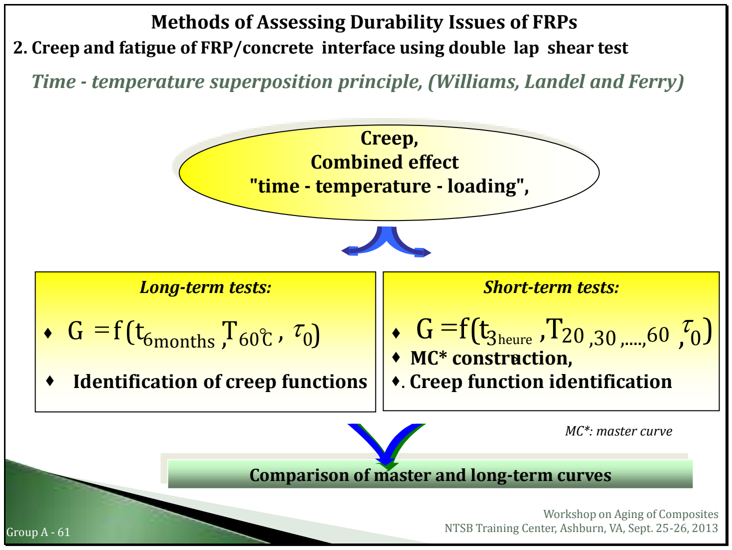

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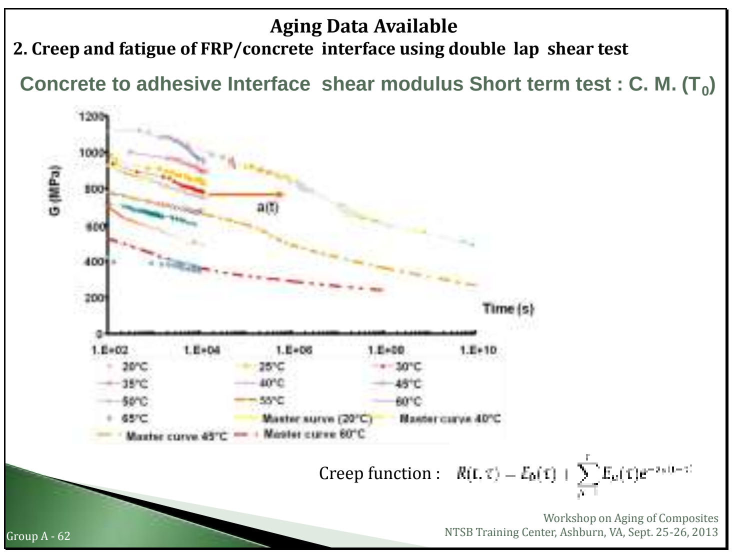

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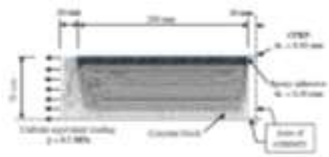
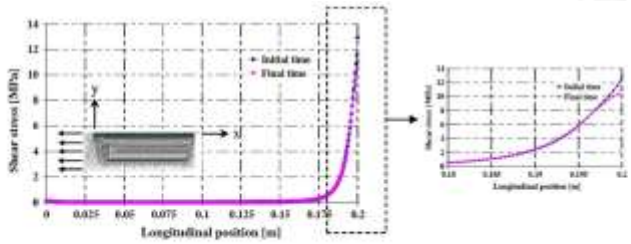
Aging Data Available

Concrete to adhesive Interface: Effect of creep FEM modeling

Stress redistribution from FRP to concrete





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Sample Life Prediction Models

Evaluation of shear stress limit

$$\gamma(t,T) = \gamma_{inst} + \gamma_{creep}$$

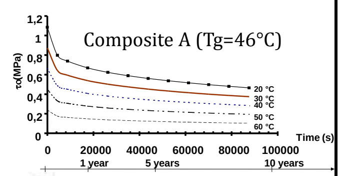
$$\gamma(t,T) = \tau_0 \cdot D(t,T)$$

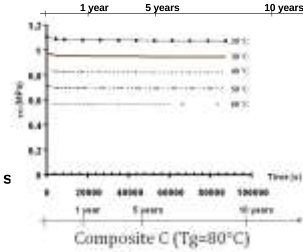
$$\tau_0 = \frac{\gamma(t,T)}{D(t,T)}$$

$$\tau_{adm} = \frac{\gamma_e}{D(t,T)}$$

τ_0 : initial shear stress; D (t,T): creep function

γ(t,T) : initial shear strain; τ_{adm} : allowable shear s
γ_e : shear strain limit





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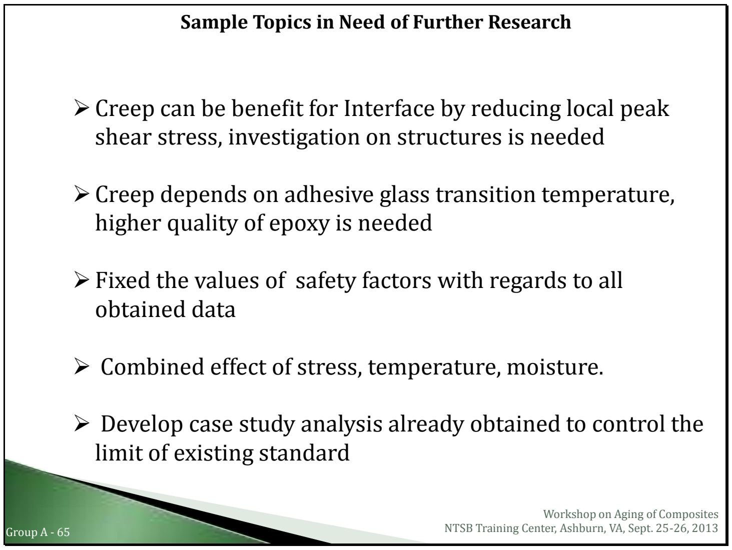

Durability Issues of Concrete Structures Strengthened with Externally Bonded FRP (EB-FRP) Composites

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Department of Civil and Environmental Engineering,
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Durability Issues of Concrete Structures Strengthened with Externally Bonded FRP (EB-FRP) Composites

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Summary

Development of externally bonded FRP (EB-FRP) systems has been a major breakthrough in the strengthening of concrete structures over the past three decades. Its popularity is increasing with the tremendous needs of maintaining and upgrading the serviceability and safety of concrete structures. In general, there are two categories of EB-FRP strengthening applications: (1) bond-critical application, in which the bond between EB-FRP and concrete is a critical issue; and (2) contact-critical application, in which the rupture of FRP is a more critical concern. This presentation outlines the durability issues of the above two types of applications. The contents consist of a brief summary of critical issues of the long-term durability of EB-FRP system in strengthening of concrete structures, important aging data that are available, and test methods and methodology for assessing the local and global degradation. The author's perspectives on the areas for further research are also illustrated. The presentation particularly focuses on the research efforts in Japan, Hong Kong and Mainland China.

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Overall summary of critical durability issues

- **FRP Materials**
  - **Chemical resistance:** cementitious matrix /alkali environment; Water/salt water; Acid; Other solutions like gasoline, toluene
  - **Mechanical resistance:** Strength/stiffness degradation; Fatigue; Creep and relaxation
  - **Thermal resistance:** Elevated temperature; Low temperature; Freeze and thaw; Fire resistance
  - **Others:** UV degradation; electro-magnetic exposure; radioactive exposure
- **FRP-to-concrete interfaces (bond-critical applications)**
  - **Mechanical resistance:** sustained load, fatigue
  - **Moisture resistance:** water immersion, dry/wet cycling, freeze and thaw
  - **Thermal:** low temperature, elevated temperature, fire
  - **Combined:** synergetic mechanical/environmental actions
- **FRP-confined concrete/reinforced concrete (contact-critical applications)**
  - **Mechanical:** sustained load, cyclic loading
  - **Thermal:** low temperature, elevated temperature, fire
  - **Others:** corrosion

For contact-critical applications, the durability issue is more relevant to the behavior of concrete and internal steel reinforcement under the protection of FRP confinement

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Overview of durability research activities in Japan

- In Year 2000, Association for Advanced Composites Technology on Construction Field (ACC) published "Investigation and Examination on the Durability of Concrete Members using FRP" based on a review of 230 technical papers. The contents covered chemical resistance, mechanical resistance, thermal properties etc. The results were mainly based upon accelerated laboratory tests.
- Since late 1980s , there has been a steady increase of the applications of FRP reinforcement as the replacement of steel reinforcement in industry-funded demonstration projects.
- Since the Great Hanshin Earthquake in 1995, there has been a rapid increase in the use of externally bonded FRP for seismic retrofit of existing concrete structures.
- Since Mid-1990s, there have been some well-planned long-term exposure tests for both internal and external FRP reinforcement as well as for the FRP-to-concrete bond.

Dr Tamon Ueda's view:

(1) FRP applications in civil engineering in Japan have not experienced long enough time.
(2) Even though there are some deterioration found in applied FRP systems, these deterioration is less likely to cause significant structural damage/collapse.

My overall view:

(1) The durability of FRP materials may not a critical issue for FRP-strengthened concrete structures. The durability of FRP-to-concrete bond and concrete/steel reinforcement under the protection of FRP should be a major concern.
(2) There is no explicit durability acceptance criterion existing for FRP-strengthened concrete structures. It is the time that we should review carefully tremendous research efforts and practical applications completed in the past two decades.

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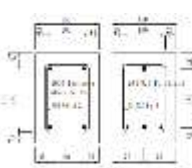
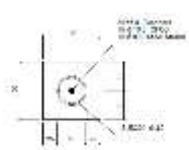
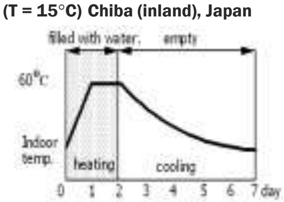
Aging Data Available: FRP tendons



Field exposure Izu Peninsula (seaside), Japan (T = 15°C) Chiba (inland), Japan





Accelerated exposure **April 1999~ (a 15-year plan)** **Fatigue tests after exposure**

Watanabe, Nakai, Enomoto &Uomoto (2012)

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Aging Data Available: FRP cables

Table 1 Detail of the FRP cables used in the test

Code	CFRP1	CFRP2	AFRP1	AFRP2	GFRP	VFRP
Shape	Strand	Rod	Rod	Woven	Rod	Rod
Fiber type	Carbon	Carbon	Aramid	Aramid	E-Glass	Vinylon
Matrix resin	Epoxy	Epoxy	VE	Epoxy	VE	Epoxy
Vf (%)	64	65	66	65	65	72
Diameter (mm)	12.5	8.0	6.0	8.0	6.0	6.0
Ultimate load (kN)	141	70.8	52.4	65.4	36.3	19.6
Modulus (GPa)	145	168	55.6	62.1	52.0	28.6
Anchor system	Adhesive	Wedge	Adhesive	Adhesive	Adhesive	Adhesive

- **SEM, FT-IR Microscopy, and DSC analyses after exposure**
- **Residual tensile load**

17 years exposure (1994~2011) Nishizaki and Sasaki (2010, 2012)

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Aging Data Available: Pultruded FRP plates and FRP sheets

Exposure locations	Latitude	Annual mean temperature	Annual mean rain fall	Climate
Sherbrooke (Quebec, Canada)	45°37'N	4.1°C	1084mm	Cold and covered with snow in winter
Tsukuba (Ibaraki, Japan)	35°67'N	13.6°C	1505mm	Moderate climate
Oogimi (Okinawa, Japan)	26°48'N	22.4°C	2036mm	Subtropical climate, close to sea shore

- Tensile properties of in pultruded direction
- Tensile properties in the direction 90^0 to that of pultrusion
- In-plane shear properties

10 years exposure of FRP sheets Nishizaki, Labossiere, Neale, Demers and Tomiyama (2011)

Name of site	Locations	General description
Rikubetsu	43.4⁰N., altitude: 310m	Subarctic zone
Tsukuba	36.0⁰N., altitude: 25m	Mild climate
Asagiri	35.2⁰N., altitude: 920m	Japanese mountain area
Oogimi	26.6⁰N., altitude: 5m	Subtropical climate

11 years exposure of FRP plates Nishizaki, Sasaki and Tomiyama (2012)

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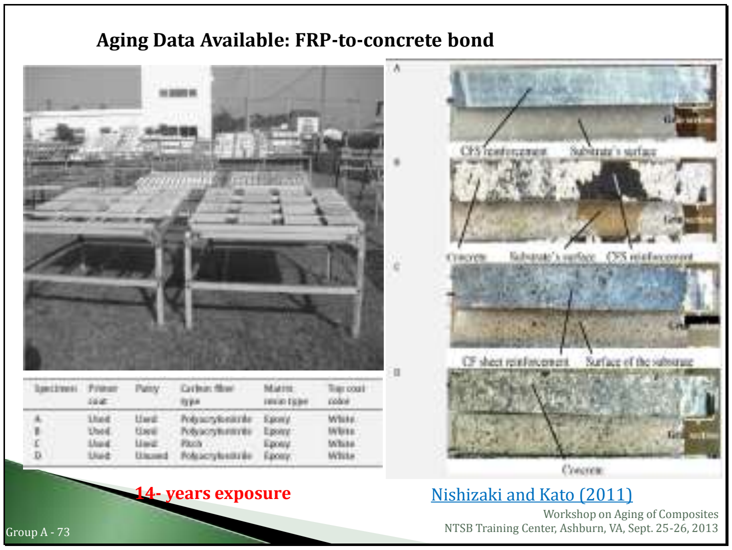

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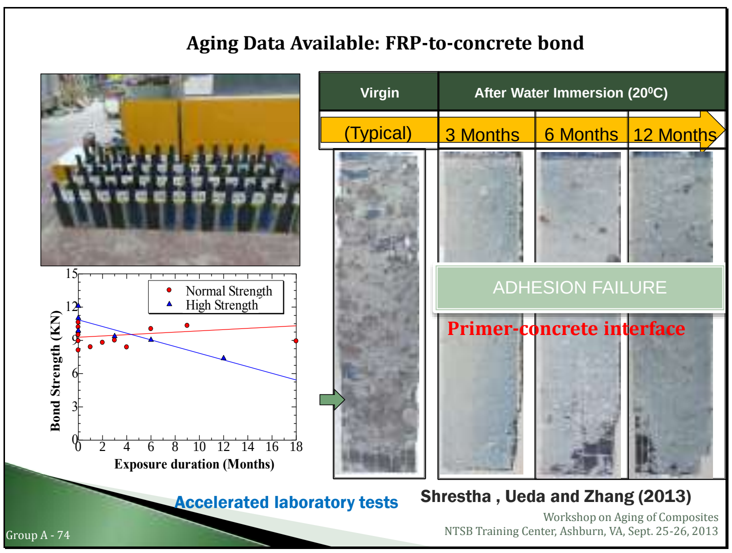

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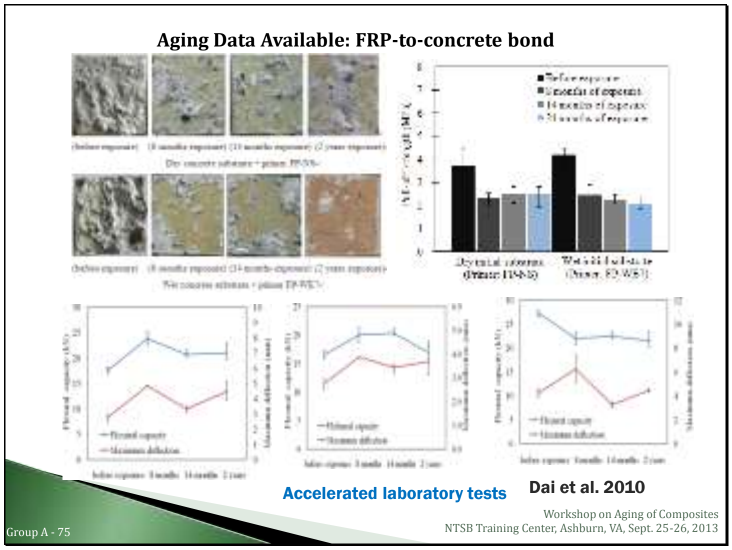

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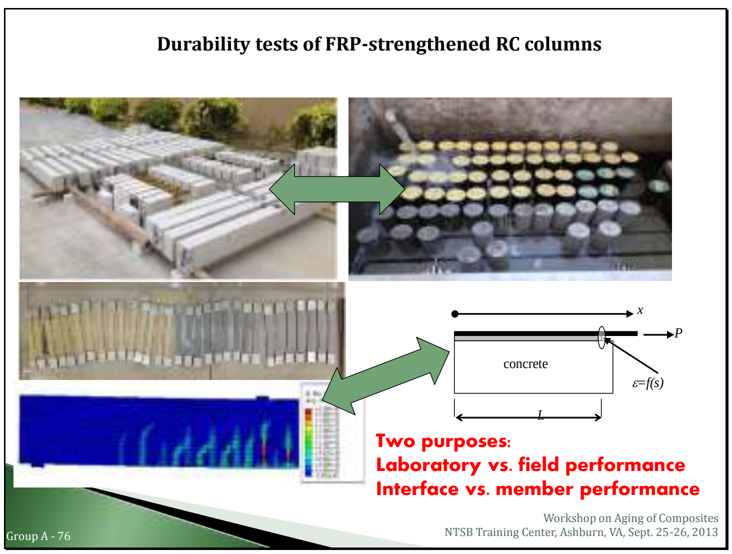

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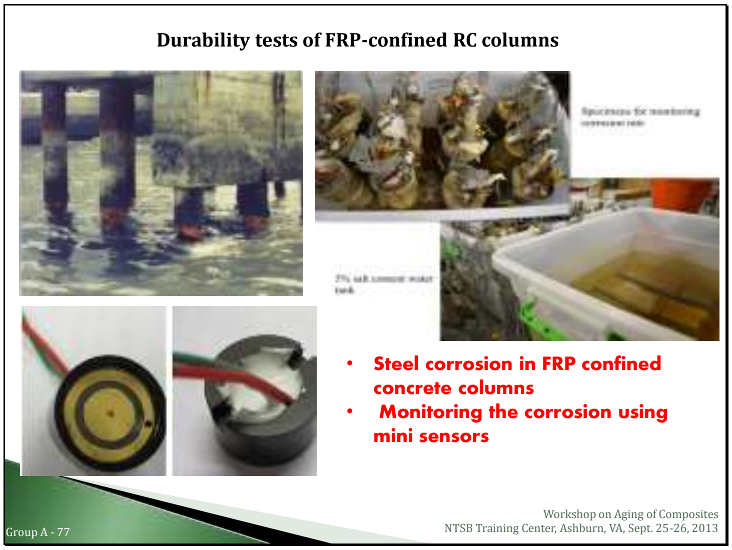

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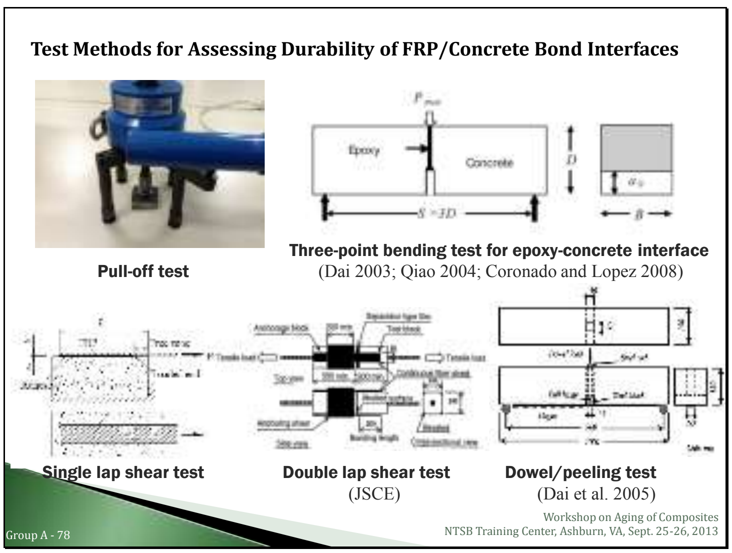

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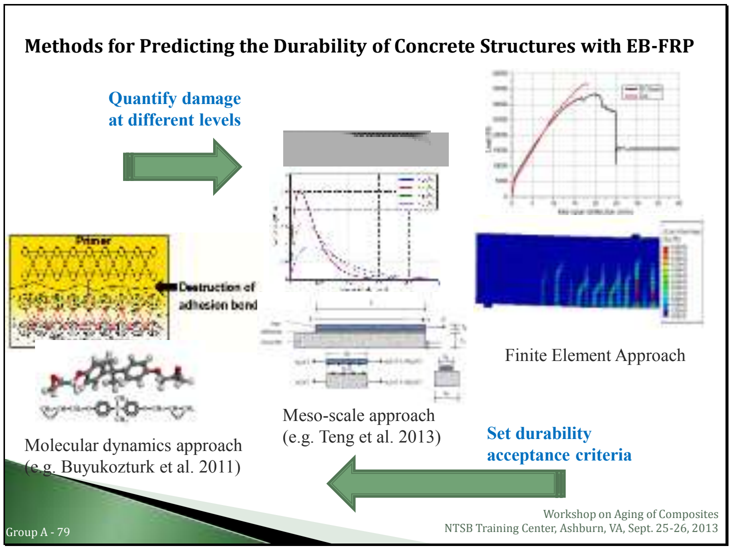

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Areas for future research

- **Durability of FRP materials and adhesives**
  - Effect of sample size on durability test results;
  - Development of moisture-resistant bonding adhesives;
  - Nano-technique enhanced epoxy for improvement of long-term bond performance;
  - Development of inorganic resins for improved fire resistance
- **Durability of FRP-to-concrete bond**
  - Exposure-dependent bond-slip model
  - Effects of initial stresses induced during the accelerated exposure on the test results
  - Effects of pre-conditions of concrete substrates on bond durability
  - Molecular dynamics approach for prediction of bond degradation
- **Durability of FRP-strengthened concrete members**
  - Correlation between the local bond degradation and global structural performance degradation
  - Effect of FRP intervention on durability of existing concrete structures
  - Theoretical approaches for structural durability prediction
- **Durability tests and durability design**
  - Database review and standardization of accelerated test methods
  - Similarity of laboratory and field environments
  - Round robin durability tests at a global scale
  - Explicit durability design criteria and monitoring techniques

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Oregon DOT Experience with FRP

Bruce Johnson (Bruce.V.Johnson@odot.state.or.us)
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International Workshop
Aging of Composites

Oregon DOT Experience with FRP

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Oregon DOT Experience with FRP

Bruce Johnson (Bruce.V.Johnson@odot.state.or.us)
Oregon DOT Bridge Section, 4040 Fairview Industrial Dr SE, MS#4, Salem, OR 97302

Oregon DOT has conducted research on the use of FRP composites for shear strengthening and on durability of FRP composite materials. We have used FRP composite materials for bridge components, FRP wraps and strips used to strengthen or reinforce concrete.

Oregon DOT's primary interest in the use of FRP in bridges has been for strengthening and rehabilitation of existing bridges. However, ODOT has used GFRP reinforcement in one new bridge application.

The presentation will cover:
1. Research on FRP composites
2. Bridge applications using FRP composites
3. Inspection and assessment or performance of FRP applications
4. Conclusions and recommendations

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Completed Research

1. **Capabilities of Diagonally-Cracked Girders Repaired with CFRP**
   - **June 2006, Chris Higgins, Oregon State University**
2. **Environmental Durability of Reinforced Concrete Deck Girders Strengthened for Shear with Surface-Bonded CFRP**
   - **May 2009, Chris Higgins, Oregon State University**
   - **Freeze-thaw applications reduce shear panel stiffness and capacity due to increased de-bonding**
   - **Long term moisture exposure reduced the contribution of CFRP to the overall member strength**
   - **ACI 440 environmental reduction factors do not fully account for losses in stiffness and strength**
3. **Shear Repair Methods for Conventionally Reinforced Concrete Girders and Bent Caps**
   - **December 2009, Chris Higgins, Oregon State University**

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Summary of Environmental Results

- Moisture at CFRP-concrete bond interface reduced strength
- Freeze-thaw cycling without moisture did not reduce strengths
  - Some T-specimens subjected to freeze-thaw exposure exhibited significant strength reduction
  - IT specimens did not exhibit freeze-thaw degradation because moisture was not able to infiltrate the free ends
- Fatigue combined with Freeze-Thaw increased debonding but did not reduce strength
- Epoxy injection kept moisture from freely moving through section

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Summary of Environmental Results

- ACI-318 and ACI-440 provided conservative shear strength predictions
- The ACI 440 specified environmental factors were not sufficient to provide uniform levels of safety. Environmental exposure factor should always be applied to limit the effective CFRP stress/strain
- Locations with very large numbers of wet freeze-thaw cycles and extended exposure to continuous moisture may warrant even smaller environmental exposure factors

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Oregon DOT FRP Applications

- **Girder shear strengthening with CFRP Strips — 32 Bridges**
- **Pier cap shear strengthening with CFRP Strips — 12 Bridges**
- **Girder flexure strengthening with CFRP Strips — 8 Bridges**
- **Modular FRP bridge decks — 4 Bridges**
- **Deck strengthening with NSM CFRP rods — 4 Bridges**
- **Deck strengthening for rail LL with NSM CFRP Rods — 4 Bridges**
- **GFRP Reinforcement — 2 Bridges**
- **Pier cap flexure strengthening with CFRP Strips — 1 Bridge**
- **Arch rib strengthening with CFRP Strips — 1 Bridge**

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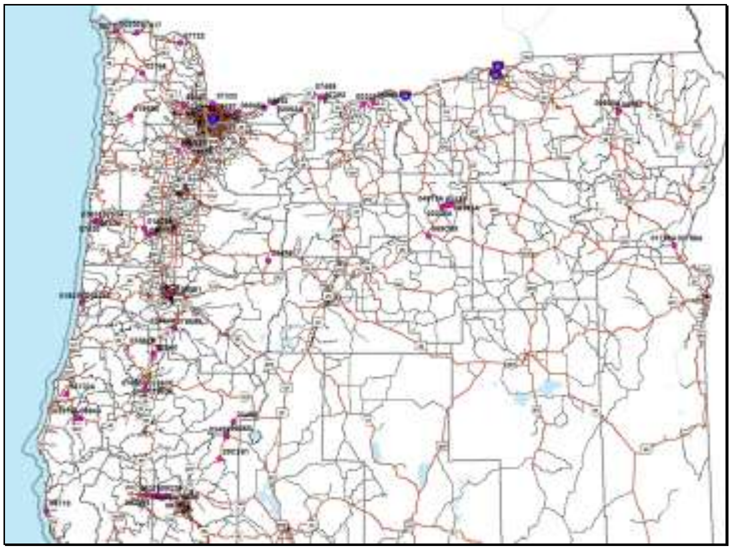

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Methods of Assessing Durability Issues of FRP

1. Visual – bulging, separations, fretting, discoloration
2. Sounding – tapping, rotary percussion tool,
3. NDT - IR Thermography
4. Check sources of moisture getting behind FRP

Age of ODOT Installations

1. FRP Shear and Flexure Strengthening	1998
2. FRP Decks	2006
3. NSM FRP	2008
4. GFRP Reinforcement	2010

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Inspection and Assessment of FRP Durability

- Overall, FRP laid up construction is performing well in a variety of environment and loading cases.
- We have found a few isolated cases of small delaminations, corners peeling away, gaps on the edges of laid up construction, voids or trapped air bubbles.
- ODOT has had significant problems with early FRP deck modules, such as seam Separation, attachment failure, wearing course adhesion, cracking
- NSM FRP is universally performing well

Group A - Slide 90

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Group A - Slide 91

Topics for Further Research

1. CRFP Surface-bonded specimens with lower transverse steel shear contributions should be investigated to enable shear failure with increased CFRP shear contribution.
2. CRFP Surface-bonded specimens should be tested with minimum transverse steel requirements.
3. Specimens should be precracked prior to application of CFRP, as this is representative of field applications.
4. Specimens should be reloaded after strengthening, to produce recracking prior to environmental exposure.
5. Specimens should be strengthened and be subjected to freeze-thaw exposure in the orientation that reflects field conditions.
6. Additional data are needed for combined environmental exposure and fatigue loading.

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Topics in Need of Further Research

1. Constructability details for FRP tied arch hangers and suspenders for suspension bridges
2. Constructability details for FRP cable-stayed bridges
3. Constructability details for FRP external post-tensioning repairs
4. Development lengths for FRP strand in prestressed girders
5. Prestress losses for FRP strand in prestressed girders
6. Ways to eliminate the crack in the wearing surface over butt joints in the top sheet of FRP decks
7. Better attachment details for FRP decks

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Group B: FRP Shapes

Chair: David Scott

Aging Studies of FRP Composites at WVU-CFC

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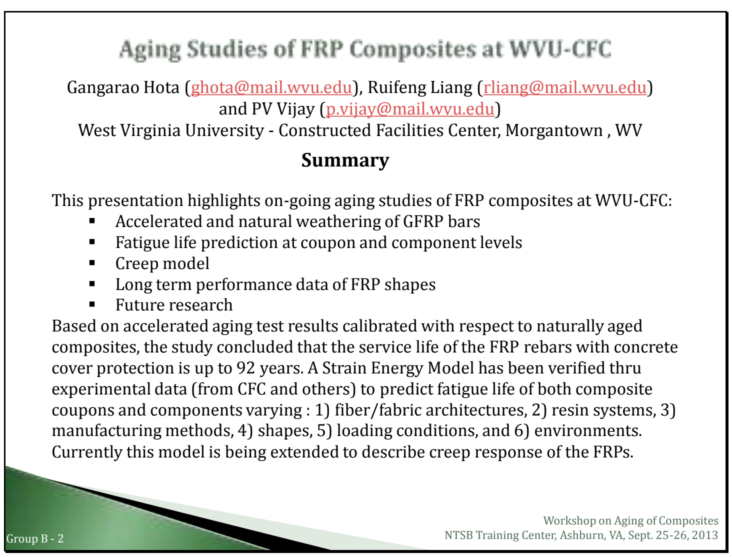
West Virginia University - Constructed Facilities Center, Morgantown , WV

Group B - Slide 1

Group B - Slide 2



Group B - Slide 3

Conditioning and Testing of FRPs

- Immersion bath
  - ✓ pH (salt, sea water)
  - ✓ Temperature
- Humidity/Temperature
- Sustained load
- Freeze-thaw
- Fatigue/Creep
- UV
- Combination of above

- Lab accelerated aging
- Field (natural) weathering
  (time: ranged from months to years)

- Tension/compression
  - ✓Static
  - ✓Fatigue
- Bending
  - ✓Static
  - ✓Fatigue
- Creep
- Fire

Group B - Slide 4

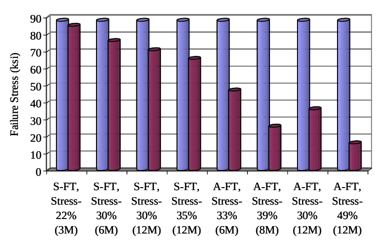
Rebar in Alkaline Environment

Aging study of Glass Fiber Reinforced Polymer (GFRP) bars up to 3 years (1999) to evaluate Strength and Stiffness properties under:

- Salt and Alkaline Conditioning without Stress
- Salt and Alkaline Conditioning with Stress (20% to 50%)
- Salt and Alkaline Conditioning with Stress and Freeze-thaw (12 to 120^{0}F)

Conclusion: Alkaline conditioning was more detrimental to the strength of GFRP bars over salt conditioning. Increasing temperature and stress resulted in strength reduction of GFRP bars.

Tensile stress reduction of GFRP rebars under different conditioning with sustained load



S:Salt A:Alkaline RT:Room Temp. FT:Freeze-Thaw M:Months

Vijay and GangaRao, 1999

Group B - 4

ging of Composites
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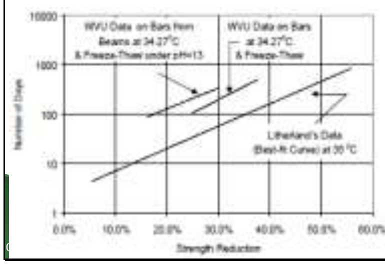
Group B - Slide 5

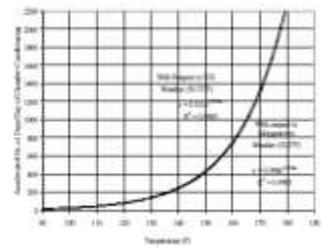
Accelerated and Natural Weathering of GFRP Bars

An accelerated aging test methodology was based on Arrhenius temperature relationship to predict aging of FRP bars embedded in concrete. The ATM data was correlated with the data from natural aging of GFRP bars:

Age in Natural Days/Days of Chamber Conditioning (y) = 0.098 $e^{0.0558T}$
where, T=Temperature in ^{0}F

- Without stress, chamber weathering of 30 months in alkaline conditioning corresponded to natural weathering of ~ 85 years at Morgantown, WV;
- With 20% sustained load, chamber weathering of 30 months in alkaline conditioning and select freeze-thaw temperatures corresponded to natural weathering of ~ 59 years.





Group B - Slide 6

Fatigue-Life Prediction Using Strain Energy Model

WVU-CFC team (Natarajan et al, 2005; Dittenber and Hota, 2010) developed a strain energy model using strain energy release rate as the damage metric to predict fatigue life of a composite material for given constituent material properties and loading conditions. This model has been extensively verified through 500 plus data (coupon and component) from WVU-CFC and others including DOE/MSU fatigue database.

- Energy release rate (Slope = dU/dN) throughout stage II is nearly linear
- Relationship between release rate and loading conditions:

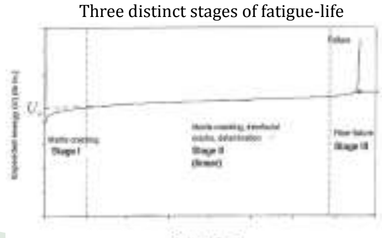
$$\frac{dU}{dN} = a\left(\frac{\varepsilon_{max}}{\varepsilon_{ult}}\right)^b$$

a and *b* are material and load-dependent constants

- **Fatigue Life Prediction Model**

$$N_f = \frac{U_f - U_o}{a\left(\frac{\varepsilon_{max}}{\varepsilon_{ult}}\right)^b}$$

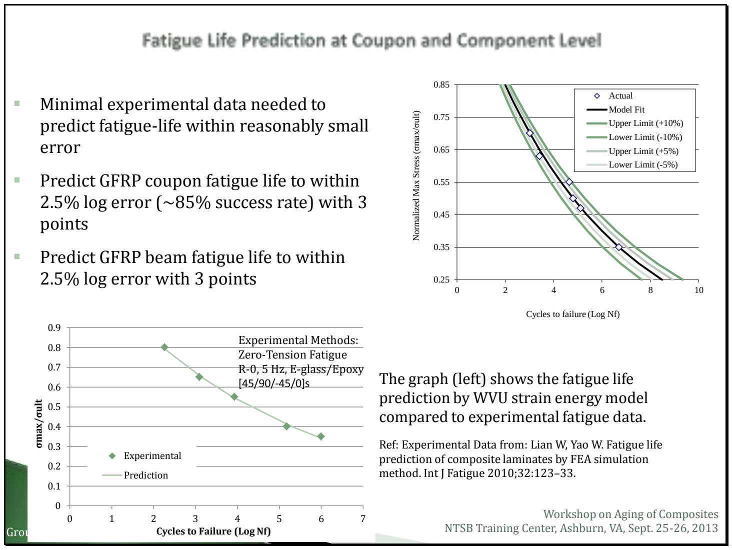
Three distinct stages of fatigue-life



- 6

CONSTRUCTED FACILITIES CENTER
West Virginia University
Center for Integration of Composites into Infrastructure

Group B - Slide 7



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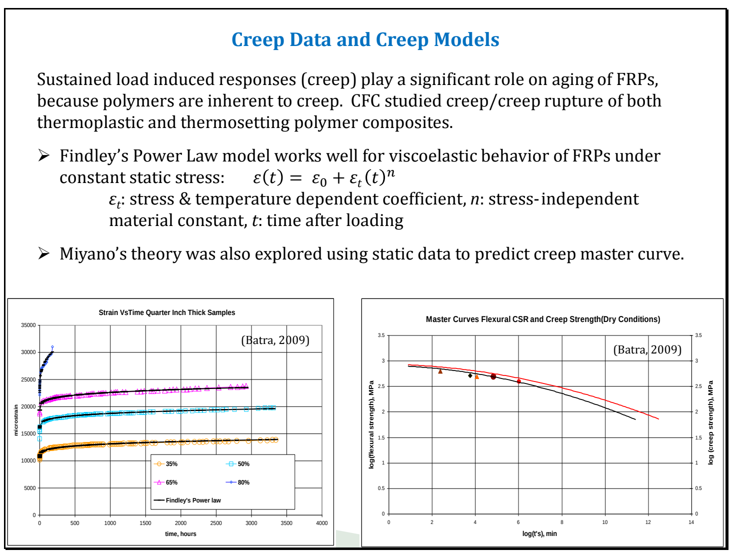

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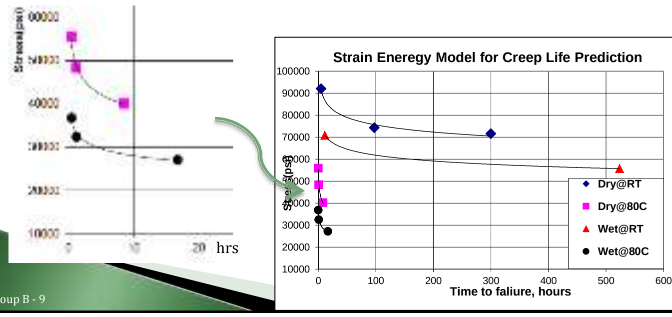
Strain Energy Model for Creep Life Prediction

CFC Creep Life Prediction Model uses Strain Energy concept. Creep test can be treated as a special case of fatigue where max and min loads are similar to R = 1 and *f*=0 hz in the fatigue response equation development; however experimental constants will be arrived at as a function of time and induced stress level. This theoretical model development is being carried out using existing data in literature and new data are needed for broad validation.



Group B - 9

Group B - Slide 10

Baseline Aging Effects on Mechanical Properties of FRP Shapes (NSF Work)

In order to assess the currently available real-time aging data of pultruded FRP shapes, coupons were cut from 15 differently aged (up to 20 years) pultruded sections.

These coupons were tested in tension, bending, and short beam shear:

• Average flexural strength LW	50.51 ksi
• Average flexural modulus LW	2.39 msi
• Average tensile strength LW	46.02 ksi
• Average tensile modulus LW	3.45 msi
• Short beam shear strength LW	3917 psi
• Average fiber fraction	60.7wt% or 43.9 vol%

- In many of the older materials, the tensile and flexural properties seem to have improved marginally with aging, potentially indicating additional curing .
- The short beam shear strength data exhibit higher age-induced reduction effects than tension or flexure data, i.e. matrix-driven reduction in interlaminar shear strength.

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Baseline Aging Effects on Short Beam Shear Strength of FRP Shapes

Aged/original short beam shear property comparison

Material	Manufacturer, Original Section, Year	Aged Strength (psi)	Original Strength (psi)	A/O Strength
#1	CP, 4" box beam, 1993	4237		
#1 transverse		1859		
#2	CP, 4x4" I-beam, 1992	3330		
#2 web		2615		
#3	BRP, 5" C-channel, 2004	5049	8177	62%
#3 web		5003	8177	61%
#4	BRP, 4x6" box beam, 2002	4339	5230	83%
#4 transverse		2814		
#5	CP, 6x6" I-beam, 2002	3778	8366	45%
#5 web		3335	5284	63%
#6	CP, 4x4" box beam, 2002	4172	5509	76%
#6 transverse		2417		
#7	SW, 2x2" box beam, 2005	5148		
#7 transverse		1939		
#8	CP, 4x4" box beam, 2002	4338	7310	59%
#8 transverse		2172		
#9	BRP, 4x4" I-beam, 2005	4502	5040	89%
#9 web		4950	4690	106%
#10	SW, 4x8" Extren I-beam, 1995	4239		
#10 web		2638		
#11	BRP, 4" Prodeck 4, 2004	3906	4287	91%
#11 transverse		3118		
#12 (sun side)	BRP, 1" sandwich, 3/4" balsa, 2003	4176		
#12 sun/trans		4029		
#13	SW, 6x9" box beam, 2009	3205		
#13 transverse		1409		
#14	SW, 8x4" Extren I-beam, 2009	2551		
#14 web		2677		
#15	BRP, 3x3" box beam,	4332		
#15 transverse		2778		

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Future Research Topics

- Develop standard durability test methods including creep
- Develop service life prediction models including degradation rate in properties
- Validate time-temperature super-position principles
- Arrive at standard procedure to determine reliable resistance factors from limited test data
- Standardize data collection after harvesting samples from in-service structures
- Establish minimum performance requirements related to durability
- Explore synergistic effects under multiple environmental factors and loading conditions
- Develop unified life prediction models for infrastructure applications using composites including manufacturing and construction variables

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Composite Anti-Collision Bumper Systems and Their Durability under Multi-Environmental Factors

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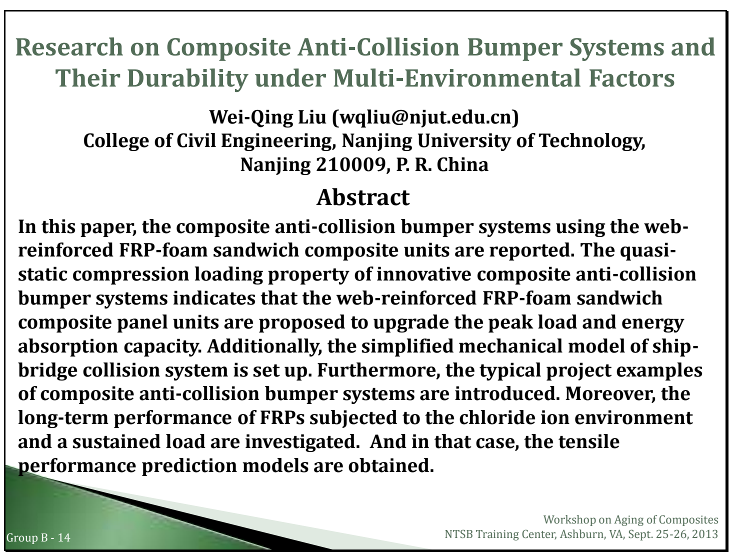
Group B - Slide 14



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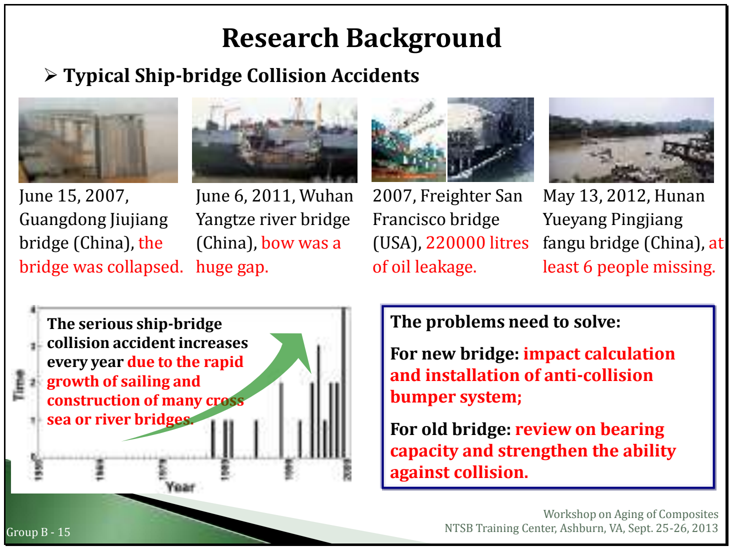

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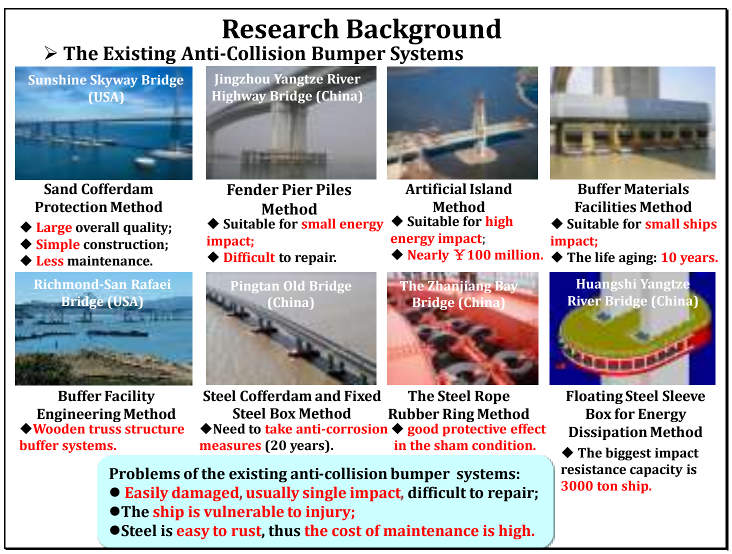

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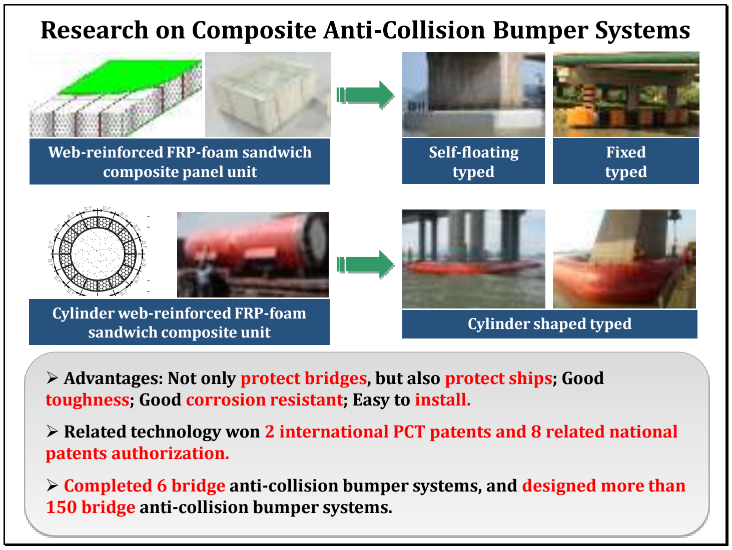

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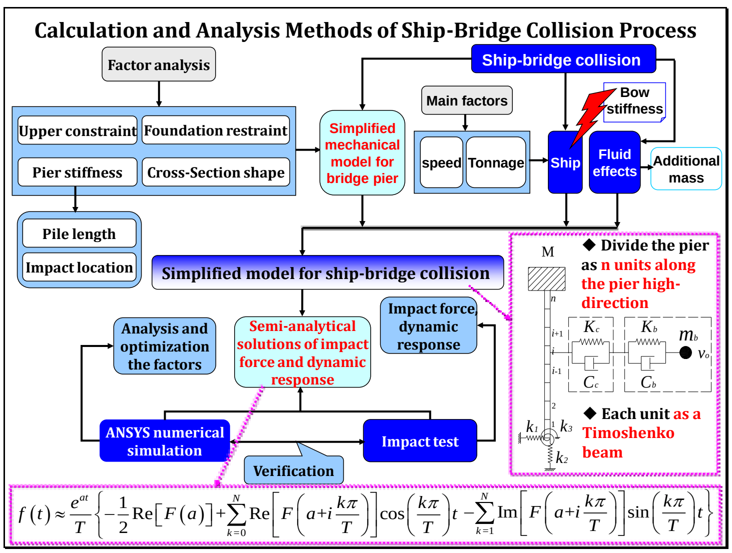

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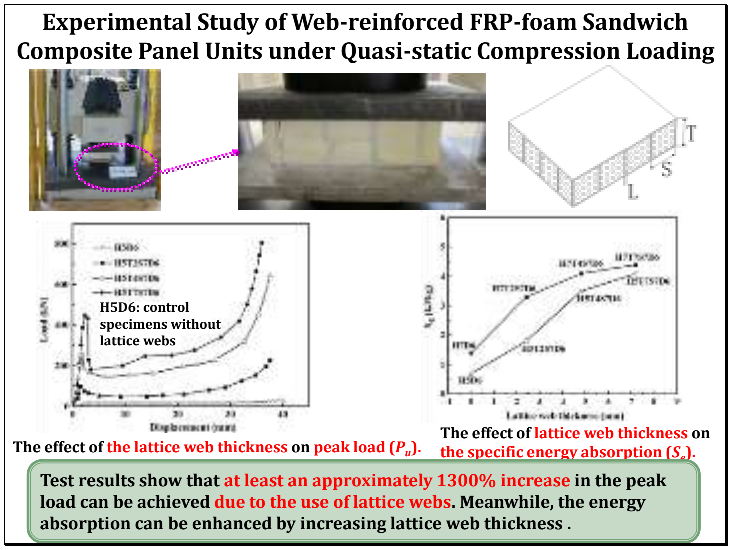

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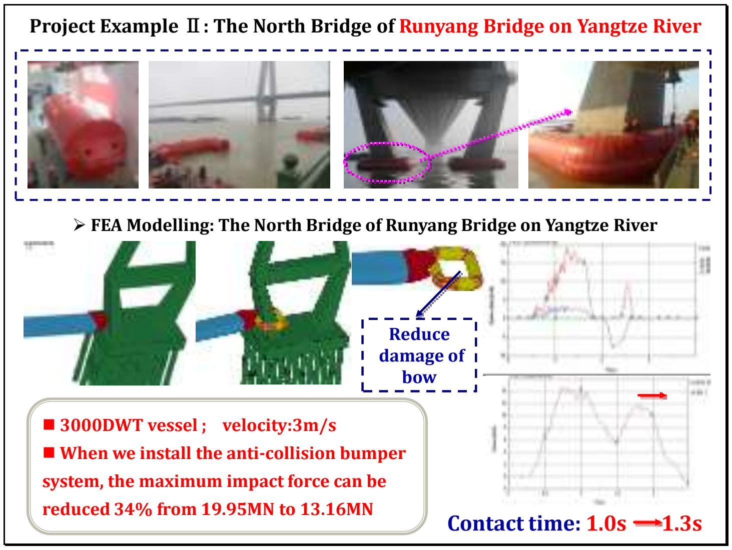

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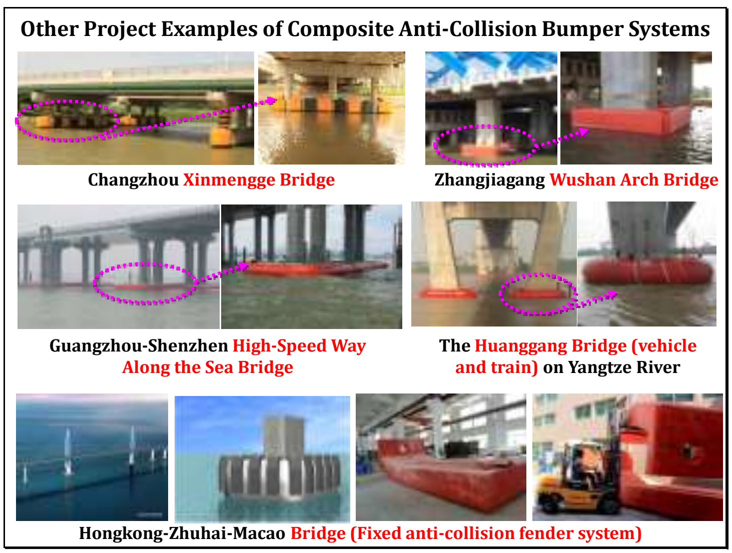

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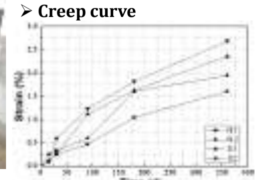
Long-term Performance of FRPs Subjected to the Chloride Ion Environment and a Sustained Load

Stainless steel tank built for aging of the GFRP specimens.

➢ **Creep curve**



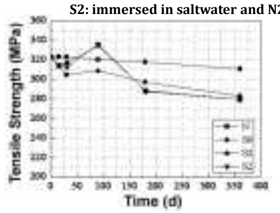
N1: 10% of the ultimate tensile strength;
N2: 20% of the ultimate tensile strength;
S1: immersed in saltwater and N1;
S2: immersed in saltwater and N2

➢ **SEM measurements**

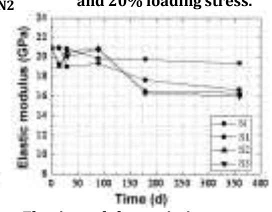
SEM micrographs FRPs after 180 days aging subjected to chloride ion and 20% loading stress.

Specimen immersed for 90 d

Specimen immersed for 180 d



Tensile strength variation curves.



Elastic modulus variation curves.

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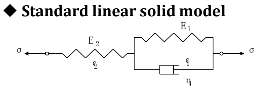
Tensile Performance Prediction Models of FRPs Subjected to the Chloride Ion Environment and a Sustained Load

➢ **Elastic modulus prediction model**

◆ **Standard linear solid model**



◆ **Wiederhorn empirical formula**

$$V = ax^f \exp(-\frac{E}{RT})\exp(\frac{b\sigma}{RT}) \quad (2)$$

$$E(t) = \frac{k_1 k_2}{k_1 + k_2} + k_2(1 - \frac{k_1}{k_1 + k_2})e^{-\frac{k_1 + k_2}{\eta_1}t} \quad (3)$$

Fitting the relationship of strain, elastic modulus, and time under different environment conditions

No.	k_1	k_2	η_1	Fitting Function
S0	70.22834	20.78689	15888.04097	$E(t) = 16.03939 + 4.74750e^{-0.00573t}$
S1	30.59654	20.68818	22685.40716	$E(t) = 12.34260 + 8.34558e^{-0.00226t}$
S2	29.32239	20.62779	21046.97635	$E(t) = 12.10919 + 8.51860e^{-0.00237t}$

➢ **Residual strength prediction model**

◆ **Median aging formula**

$$S = S_0 + \eta(1 - e^{-\lambda t}) - \beta \ln(1 + \theta t) \quad (5)$$

◆ **Fitting the relationship between retention rate of tensile strength and time under different enviroment conditions;**

◆ **Using regression analysis to determine the undetermined parameters combined with experimental data.**

No.	Retention rate of tensile strength
S0	$f_{S0}(t) = 100 + 47.7(1 - e^{-0.83t}) - 16.32\ln(1 + 3.24t)$
S1	$f_{S1}(t) = 100 + 45.44(1 - e^{-0.73t}) - 15.69\ln(1 + 3.56t)$
S2	$f_{S2}(t) = 100 + 44.75(1 - e^{-0.69t}) - 15.57\ln(1 + 3.52t)$

◆ **Elastic modulus prediction model considering stress level and time**

$$E(s,\sigma) = \begin{cases} (16.040 - 38.135\sigma) + (4.748 + 35.981\sigma)e^{-(0.00573 - 0.0347\sigma)t} & (0 \le \sigma \le 10\%) \\ 12.226 + 8.432e^{-(0.00226 + 0.00055\sigma)t} & (10\% \le \sigma \le 30\%) \end{cases} \quad (4)$$

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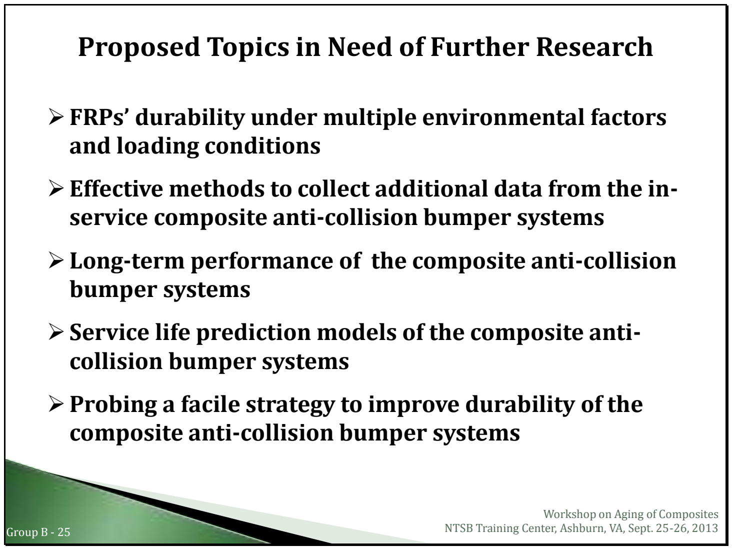

Creep of Pultruded Fiber Reinforced Polymeric Materials in Civil Infrastructure Applications

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Group B - Slide 26

Group B - Slide 27

Creep of Pultruded Fiber Reinforced Polymeric Materials in Civil Infrastructure Applications

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Fiber-reinforced polymeric (FRP) materials have demonstrated significant potential for use in civil infrastructure, including both new construction and repair. The high strength/weight ratio, resistance to many types of service exposure conditions, and tailorability of FRP materials make them an attractive alternative to traditional construction materials in a wide range of applications. However, one of the continuing challenges hindering the expanded use of these materials is the lack of well-accepted specifications and design criteria for use by practicing engineers. A fundamental understanding of the time-dependent behavior of FRP materials and structures in service is one of the core issues that needs to be addressed to allow the civil engineering community to take full advantage of the many possibilities for the use of FRP materials in infrastructure.

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Is the lack of understanding of time-dependent behavior a problem?

ACI 440.1 (2006), ACI 440.2 (2008):

Table 10.1—Sustained plus cyclic service load stress limits in FRP reinforcement

	Fiber type		
Stress type	GFRP	AFRP	CFRP
Sustained plus cyclic stress limit	$0.20f_{fu}$	$0.30f_{fu}$	$0.55f_{fu}$

Eurocomp Design Code (1996):

Safety Factor $\gamma_{m,3}$ ranges from 2.5 – 3 depending on service temperature

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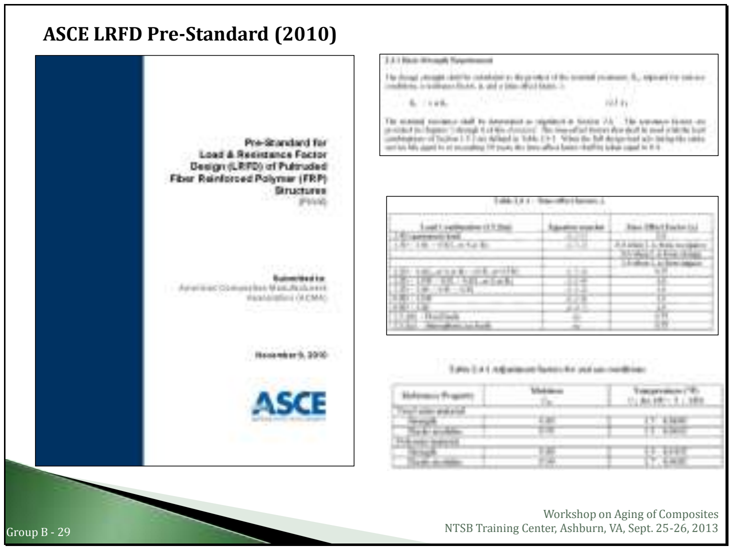

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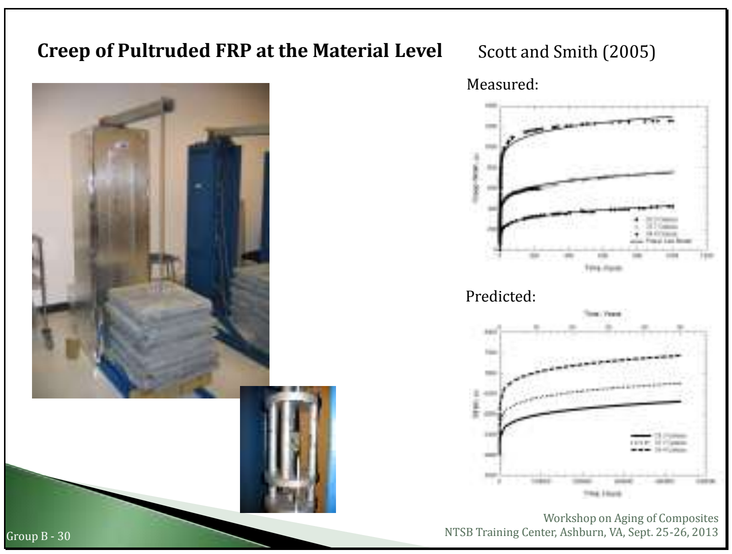

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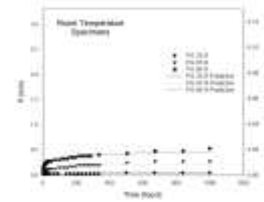
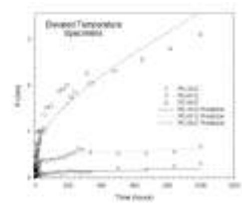
Creep of Pultruded FRP at the Structural Level Scott and Bennett (2012)





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Examples of Modeling and Design Guidance

Prediction of Lateral Deflection in Pultruded FRP columns:

$$\delta(t) = A_i \frac{\lambda[1+\psi(t)]}{1-\lambda[1+\psi(t)]} \qquad \psi(t) = \frac{t^n}{\beta}$$

Time-dependent modulus reduction:

$$E_L(T,t) \quad \phi_{(T,t)} E_L^0 \qquad \phi_{(T,t)} = \left(\frac{1}{1+0.22\sinh\left(\frac{T}{T_o}-1\right)t^{0.05}}\right) + \left(\frac{1}{1+\frac{5}{\beta}t^{0.20}}\right) - 1$$

<u>Does more “accurate” always mean more complicated?</u>

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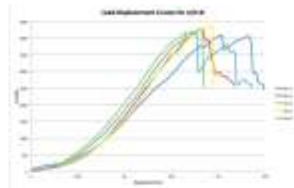
Work in Progress – Creep of Pultruded FRP Subjected to Pin Bearing



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Research Needs Related to Creep/Relaxation in FRP Materials and Systems

- Development of standardized test methods and experimental criteria for determining pertinent viscoelastic response of specific FRP material systems.
- Parametric analysis of impact of manufacturing process, constituent makeup, material layup, and other critical variables on the long-term performance of FRP materials.
- Investigation of the effect of so-called "normal" service conditions on the viscoelastic behavior of FRP materials.
- Influence of combined sustained and cyclic loads on the performance of externally bonded FRP materials.
- Correlation of multi-scale investigations of the time-dependent behavior of FRP materials to identify economical approaches for reliable assessment.
- Assessment of FRP demonstration projects in the field from a time-dependent performance standpoint.

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Aging and Durability Issues of Wood Polymer Composites

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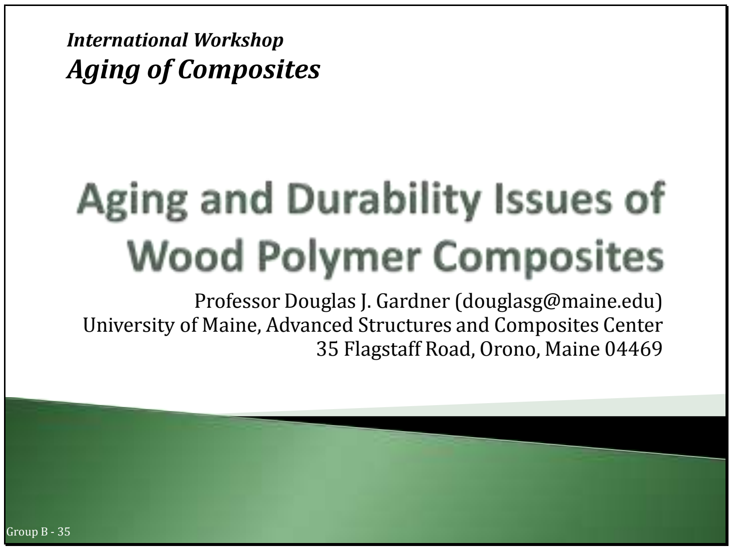

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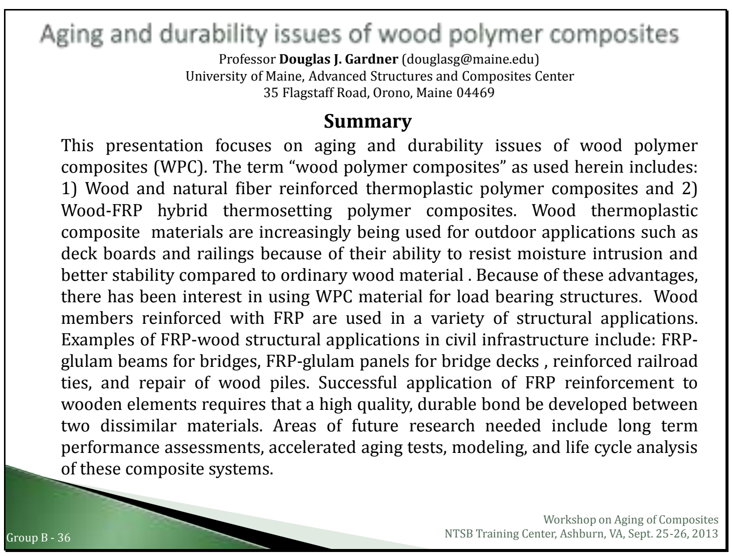

Group B - Slide 37

Overview of critical areas of durability

- **Thermoplastic-based composites (WPCs)**
- Moisture Effects
  - Reduction in strength/stiffness
- Thermal Changes
  - Thermal expansion
  - Mechanical creep
  - Thermo-oxidative degradation
- Weathering
  - UV degradation
- Biological Attack
  - Decay
  - Mold

- **Thermoset-based composites (FRP-wood bonding critical issues)**
- Type of reinforcement (Aramid, glass or carbon)
- Durable & cost-effective adhesives
- Effect of wood preservative chemicals & treatment on FRP properties
- Environmental exposure combined with loading (synergistic effects)

Group B - Slide 38

Aging data available

➢The Advanced Structures and Composites Center has worked extensively over a period of years developing models and design specifications for FRP-glulam bridges; evaluating the durability of FRP-glulam bridges through material level and full scale testing; and constructing, evaluating and monitoring FRP-glulam bridges.

➢The Advanced Structures and Composites Center has designed and monitored over 20 demonstration bridges and piers; three of which have won national awards for their innovative features.

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Aging data available

WPC Sheet pile wall installed May 2011

FRP-glulam hybrid demonstrations going back 10 to 15 years

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Methods of assessing durability issues of wood polymer composites

- Thermoplastic WPCs
- ASTM D 7031-11 Standard Guide for Evaluating Mechanical and Physical Properties of Wood-Plastic Composite Products
- ASTM D 7032-10a Standard Specification for Establishing Performance Ratings for Wood-Plastic Composite Deck Boards and Guardrail Systems (Guards or Handrails)

- Thermosets FRP-Wood
- ASTM D7199 - 07(2012)
- Standard Practice for Establishing Characteristic Values for Reinforced Glued Laminated Timber (Glulam) Beams Using Mechanics-Based Models
- JTE 2005 Performance-Based Material Evaluation of Fiber-Reinforced Polymer-Wood Interfaces in Reinforced Glulam Members

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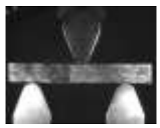
Application of the Short Beam Shear Test For Monitoring Environmental Aging Effects On Interfaces in FRP Composites

- Aqueous immersion has largest negative impact on composite interlaminar shear strength (ILLS)
- Freeze-Thaw has an intermediate effect on ILSS as a result of aqueous exposure.
- Natural and artificial weathering is a surface effect, and doesn't impact the interface to a large extent.
- The vinyl ester matrix performs very well, the vinyl ester/polyester performs fair, It is speculated that the difference in matrix response is due to differences in diffusivity and void content
- The ILSS test is a simple and discriminating indicator of interface durability



Short beam shear test (ASTM D 2344)

2000 MST Conference

Immersion Tests

Ultraviolet Exposure

Freeze-Thaw

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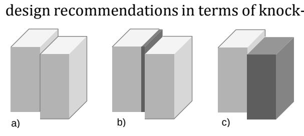
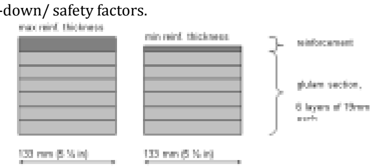
Sample Testing Recommendations for wood-FRP glulam bond interfaces

1. Modifications introduced in the ASTM D 2559 standard procedures to accommodate specifics of FRP-reinforced glulam in material level tests appear to have provided an adequate qualification protocol for FRP-wood interfaces.
2. The modified test protocol can be applied to a broad variety of wood and glulam structural members with FRP-composite reinforcement. The test protocol can also be used for comparison of compatible preservative treatments.
3. Long-term field monitoring studies are necessary to determine if the accelerated test protocol and the delamination limits can be validated for assessing durability of FRP-composite reinforcement for glulam members in exterior structural applications.
4. The limit values for the cyclic delamination test need to account for the hygrothermal stresses developed at the interface of dissimilar materials (e.g., FRP-wood, as opposed to woodwood interfaces in conventional glulams).Durability considerations of FRPs have to be integrated into design recommendations in terms of knock-down/ safety factors.



Block shear specimens for modified ASTM D2559 test.



Lopez-Anido et al. (2005) JTE.

Delamination specimens for modified Specification D2559 test.

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Sample Life Prediction Models

Tamrakar et al. (2011) used accelerated testing methodology in terms of the time – temperature super-position principle to determine the long-term creep response of a extruded wood plastic composite sheet pile:

Quasi-static and creep tensile tests were conducted at -10, 21, 30, 45 and 65 °C. The decrease in the modulus of elasticity and the modulus of rupture with the increase in temperature was characterized. Short term tensile creep tests were conducted for 40% stress level at 21, 30 and 45 °C. The time–temperature superposition principle was implemented to model the long-term creep performance at 21 °C. The long-term creep response was predicted up to 7.9 years for the WPC material.

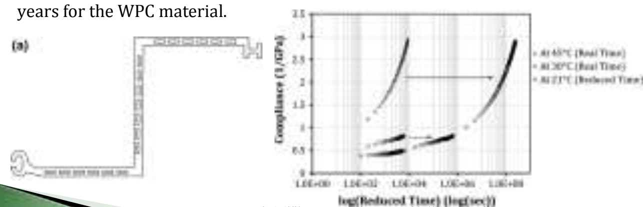

Fig. 9. Shifting creep curves for WPC material with 21 C as a reference temperature.

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Areas in need of future research

- **Thermoplastic-based composites (WPCs)**
  - Fundamental research on accelerated weathering
  - Plastics and/or reinforcements for structural WPCs
  - Long term creep issues
  - Improved weathering resistance
  - Fire resistance
  - Development of improved durable WPC formulations
    - nanofillers
  - Modeling material properties of WPC products

- **Thermoset-based composites (FRP-wood hybrids critical issues)**
- Adhesive systems that can adhere FRP to wood with no need for pre-treatments.
- Wood preservative treatment effects on FRP
- Synergistic effects in long-term performance
- Bond model for FRP-wood interfaces

Life cycle assessment

Reduce life cycle energy consumption and green house gas emissions

Review of Fibre Composite Structures in Australia

Prof Thiru Aravinthan (thiru.aravinthan@usq.adu.au)
University of Southern Queensland, Toowoomba, Australia

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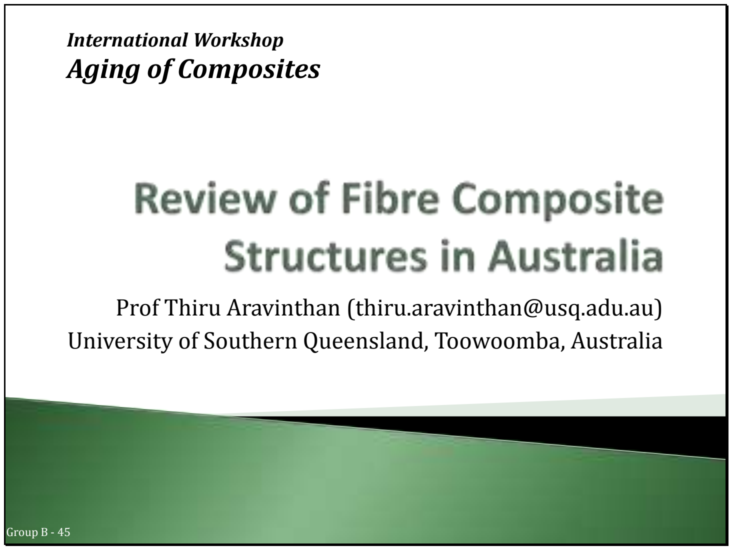

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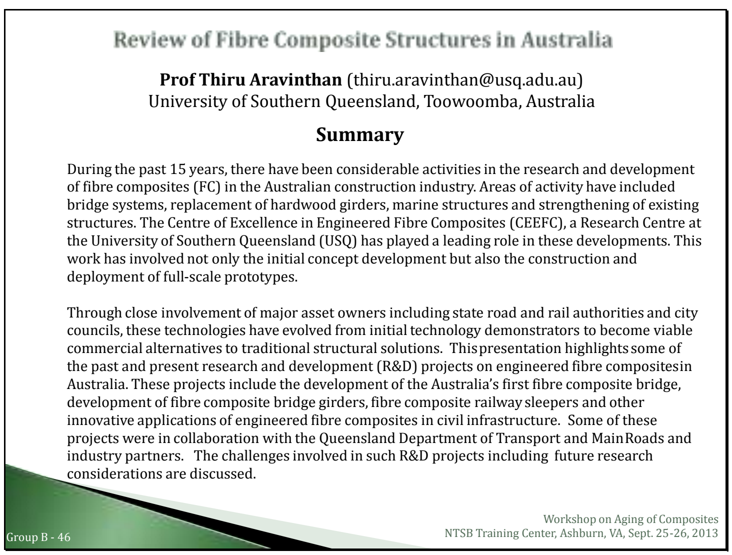

Review of Fibre Composite Structures in Australia

Prof Thiru Aravinthan (thiru.aravinthan@usq.adu.au)
University of Southern Queensland, Toowoomba, Australia

Summary

During the past 15 years, there have been considerable activities in the research and development of fibre composites (FC) in the Australian construction industry. Areas of activity have included bridge systems, replacement of hardwood girders, marine structures and strengthening of existing structures. The Centre of Excellence in Engineered Fibre Composites (CEEFC), a Research Centre at the University of Southern Queensland (USQ) has played a leading role in these developments. This work has involved not only the initial concept development but also the construction and deployment of full-scale prototypes.

Through close involvement of major asset owners including state road and rail authorities and city councils, these technologies have evolved from initial technology demonstrators to become viable commercial alternatives to traditional structural solutions. This presentation highlights some of the past and present research and development (R&D) projects on engineered fibre composites in Australia. These projects include the development of the Australia's first fibre composite bridge, development of fibre composite bridge girders, fibre composite railway sleepers and other innovative applications of engineered fibre composites in civil infrastructure. Some of these projects were in collaboration with the Queensland Department of Transport and Main Roads and industry partners. The challenges involved in such R&D projects including future research considerations are discussed.

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Fibre composite bridges

- **Australia's first fibre composite bridge**

First fibre composite bridge in Australia (2002)

Taromeo Creek Bridge - first application of fibre composites in a highway bridge in Australia **(2003)**

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Fibre composite bridges

- **Fibre composite road bridges**

Manly Road Bridge (www.wagnerscft.com.au)

Hawkesbury composite bridge (www.wagnerscft.com.au)

New generation composite bridge at USQ

Hybrid beam with plantation timber

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Fibre composite bridges

- **Pedestrian bridges and walkways**

Bowman Parade pedestrian bridge (www.wagnerscft.com.au)

Mackay Bluewater Environmental Trail (www.wagnerscft.com.au)

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Bridge beams and Decks

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Rehabilitation of timber bridges

- **Replacement composite girders to timber girders**

Fibre composite girder replacing timber bridge girders.

Concept 1 - WCFT girder

Concept 2 - CarbonLOC composite girder

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Components - Pultruded Sections

Wagners methodology is to produce modular building components from which products for Civil Industry can be manufactured.

100x100

125x125

300x25

As well as other sections sourced externally.

(www.wagnerscft.com.au)

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Components - CarbonLoc™ Sandwich Panels

(www.loklite.com.au)

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Other infrastructure projects

- **Fibre composite railway sleepers**

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Other infrastructure projects

- **Fibre composite piles**

Timber piles replacement at Shorncliffe pier, Brisbane

Composite piles for Jack Evans Boardwalk, Queensland

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Challenges and issues

- Wide options for materials and components
- Limited durability data on FRP composites systems
- Design codes and guidelines for all FRP/hybrid composite structures
- Subject to diverse environmental conditions (UV, high-temperature, bushfire etc)
- Design life requirements for different applications
- Education and training for civil/structural engineers in FRP composites

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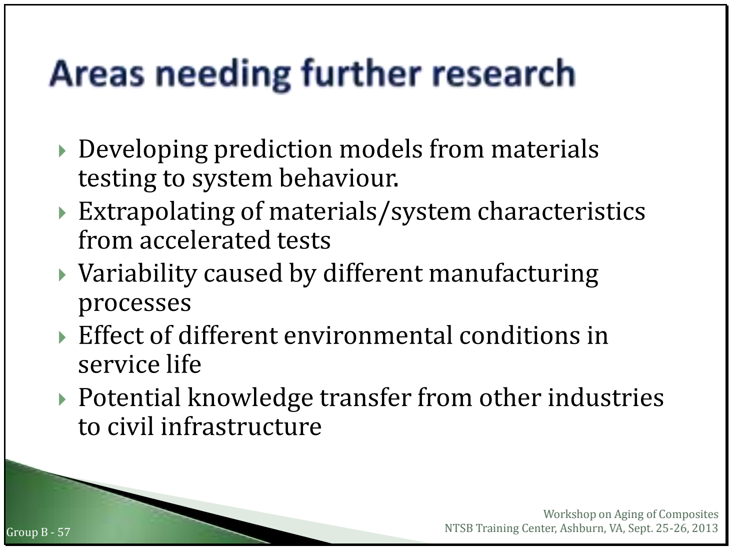

FRP Composites in Texas Infrastructure – How Long Will They Perform?

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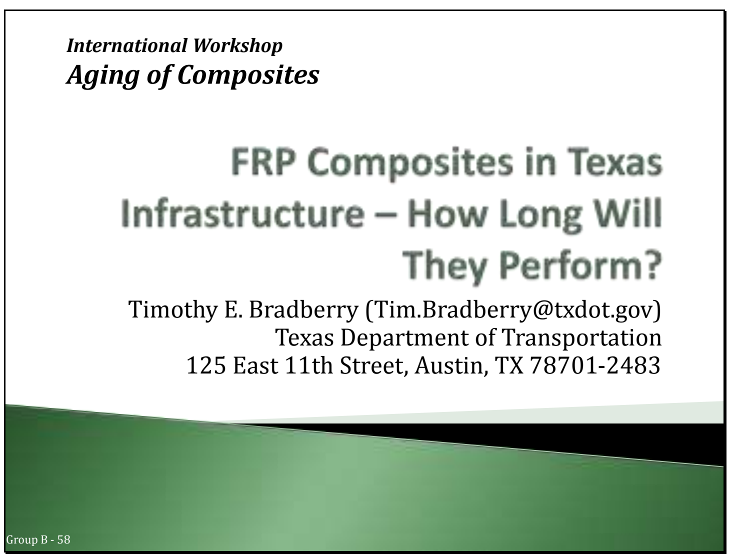

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FRP Composites in Texas Infrastructure – How Long Will They Perform?

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Abstract

Use of FRP Composites in Texas transportation infrastructure began more than 14 years ago and has progressed over time. The first, and arguably most frequent, use has been of externally bonded FRP systems for structural repair and strengthening of concrete elements. Secondly, the Department has used internal GFRP reinforcement in a bridge deck to enhance its durability. Thirdly, TxDOT and Regional Mobility Authorities have used GFRP reinforcement in pavements to provide the magnetic transparency required by electronic toll collection systems of Texas' growing inventory of toll roads.

Although TxDOT has built one FRP composite beam bridge, TxDOT bridge engineers do not consider this application very practical.

TxDOT's 2014 standard construction specifications will include GFRP rebar as reinforcement for concrete. Furthermore, the TxDOT Bridge Division is developing GFRP reinforced bridge deck standard details intended for use in the northern region of the state where deicing salt application is frequent.

The question of the sustainability of the performance of FRP composites (particularly internal GFRP bars) remains—or is perceived as—largely unanswered. In spite of the advances in normalization of GFRP in TxDOT standards, engineers remain largely ignorant of, and/or hesitant to use, this non-traditional material.

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FRP Composites Viability Statement

"Either our material [FRP composites] must do a job that no other material can do effectively, or, for the same price, they must perform better than competitive materials, or at a lower price, they must do as good a job as alternate materials, or their unique characteristics must enable the manufacturer using them to make corollary savings not possible with other materials."

- Harold Boeschenstein, a composites industry pioneer

Durability is a significant limiting factor on the competiveness of FRP Composites. In infrastructure applications to do what other materials cannot effectively do means to, at a minimum, function for the duration of expected service life. To perform better than competitive materials demands more. For example, various types of coated or stainless steel bars have promised to slow down or practically eliminate corrosion. FRP bars, which do not exhibit galvanic corrosion, must be shown to have superior service life at the same or cheaper cost if they are to compete.

The Market Development Alliance (MDA) of the FRP Composites Industry has stated: "The composites industry is working towards the development of a comprehensive database of composites durability data for materials and products used in public civil infrastructure and relevant applications."

Assuming such data are favorable toward the durability/sustainability of FRP Composites this database will move these materials toward a more competitive position as reinforcement for public civil infrastructure.

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First Structural Application of Externally Bonded FRP in Texas Bridge Infrastructure

In May 1999, an inverted T bent cap ledge was strengthened using the carbon system in a bridge application.

TxDOT engineers fist used FRP composites to solve a structural problem by externally bonding CFRP to the ends of inverted T bents in Houston to address stem to ledge intersection cracking.

Also in 1999 a large-scope project intended to mitigate ongoing corrosion of reinforcement in 16 Lubbock bridges using GFRP wraps was completed. Skeptical bridge engineers concerns included:

(1) corrosion may actually be accelerated by the wrapping; and

(2) inspectors would not be able to assess the soundness of the underlying concrete because the members were almost completely wrapped by the bonded fiberglass material.

A subsequent research project found that the glass fiber wrap was indeed effective at reducing the rate of steel reinforcement corrosion.

Regarding the bent cap application shown here, TxDOT engineers are interested in knowing just how long this CFRP is going to remain bonded or otherwise structurally effective.

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Most Frequent Use of Externally Bonded FRP in Texas Bridge Infrastructure

In January 2002, the 38 year old FM 1927 bridge over IH 20 in Ward County was struck by an over-height vehicle severely damaging the 60-ft span external girder between two diaphragms. The bottom flange and the web of the girder were fractured into several pieces leaving the concrete severely damaged but the strands retaining most of their pre-impact tension. The concrete deck, top flange and portion of the girder outside the impact area were in good shape.

The restoration work consisted of repairing the damaged concrete by conventional methods and then wrapping the girder with FRP up to the slab. The purpose of the FRP wrap was to enhance the integrity of the repair. The concrete was repaired using rapid-set non-shrink grout and concrete, and epoxy injection. The FRP wrap consisted of unidirectional carbon-fiber fabric applied in a compatible epoxy resin.

Such repairs are the most frequent usage of externally bonded FRP in Texas bridge infrastructure. Scores of such repairs have been made throughout Texas over the last decade. Although, this use of FRP composites is strictly to enhance the structural integrity of the concrete, with a secondary effect of hardening the bridges against future impact, long term efficacy of the composite material and its bond to the concrete is of concern.

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A Rare Use of Externally Bonded FRP in Texas Bridge Infrastructure

The Sue Creek Bridge on FM 1632 in Burleson County has two 30-ft spans and was built before 1964. The bridge was to be widened from its original width of 21.5-ft to an overall width of 32-ft. To be eligible for Federal funding for the widening it had to be strengthened to increase it's load rating. The two spans were strengthened with different CFRP strengthening systems.

The first span was strengthened with longitudinally oriented CFRP fabric as the primary strengthening reinforcement and with transverse CFRP fabric straps as secondary reinforcement to control debonding. The second span (shown here) was strengthened with longitudinally oriented CFRP pultruded laminates as the primary strengthening reinforcement and with transverse CFRP fabric straps as secondary reinforcement to control debonding.

Although there has been at least one repair of an impact damaged bridge in which CRCP was used to replaced the strength of a few fractured prestressing strands, this bridge is the only example, so far, in the large inventory of Texas bridges of using CFRP for flexural strengthening. Strengthening of other bridges or bridge elements have been performed but they have been to increase shear capacity.

Texas bridge engineers have more concern about the long term efficacy of the composite material and its bond to the concrete in cases of strengthening than in case where the bonded FRP is simply enhancing the structural integrity of the repairs.

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A Problem to Solve: More Than a Pot Hole

A well know Rabbi told his disciples and others that "rust doth corrupt." And of course He was right, it does and always will. Steel reinforced bridge decks are not free from the corrupting effects of reinforcing steel corrosion. This corruption creates more than a pot hole and makes the fix much more expensive than a pot hole.

A now somewhat date statistical analysis of the timing of bridge maintenance and rehabilitation, prepared for the Indiana Department of Transportation, indicates that bridges are replaced, for various reasons, at between 40 and 70 years of service life, decks are replaced at around 45 years, and in as little as 22 years some type of major deck work is required. If the service life of bridge decks could be increased to at least 50 years, prior to needing major maintenance, the associated costs of maintenance, rehab, or replacement could be deferred for as much as 28 years. If the cost of achieving this deck service life can be kept to a small fraction of the bridge construction cost, the life-cycle savings would be significant.

Nationally, studies indicate that serviceable bridge deck life averages from only 22 to 25 years where chlorides are present in the concrete. Texas was not included in these studies, however where de-icing salts are regularly applied to bridge decks in Texas, it is unlikely that many decks are in service for much more than 25 or 30 years before needing significant maintenance or repair as a result of corrosion induced deterioration.

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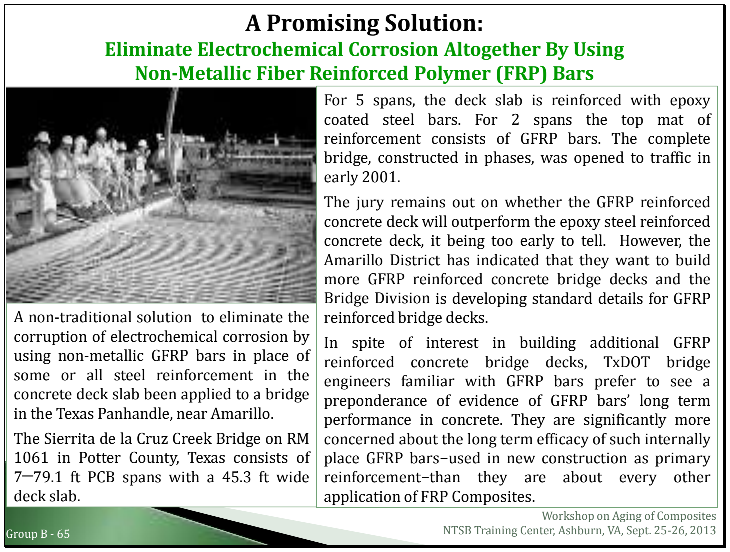

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Where FRP Composite material is most competitive is where it's needed for some unique property or properties that alternative material either cannot provide or provides at a significant premium over FRP. Such is the case with the use of GFRP dowels and/or bars in the toll collection regions of Texas tollways. Loop detectors embedded in the pavement are used to detect pertinent characteristics of vehicles passing through electronically tolled lanes. In order to function properly the magnetic field generating loop detectors require that the pavement not have magnetic field carrying / conductive elements. The non metallic / non conductive property of GFRP material is a perfect fit for this application and much cheaper than stainless steel bars.
There are a number of toll roads in Texas that have been built since 2000 that use GFRP material in this way. There have been many such installations under several toll authorities. Most have used a jointed concrete pavement (JCP) design with longitudinal GFRP dowels and transverse

GFRP rebars but at least one has used Continuously Reinforced Concrete Pavement (CRCP) design, which is what is shown in this photo.

In the case of JCP, transmitting shear force across the joints is paramount and so long term performance of the FRP dowels is important. For CRCP, crack width and spacing are the important factors and these develop in a relatively short time making long term durability of the GFRP bars less important.

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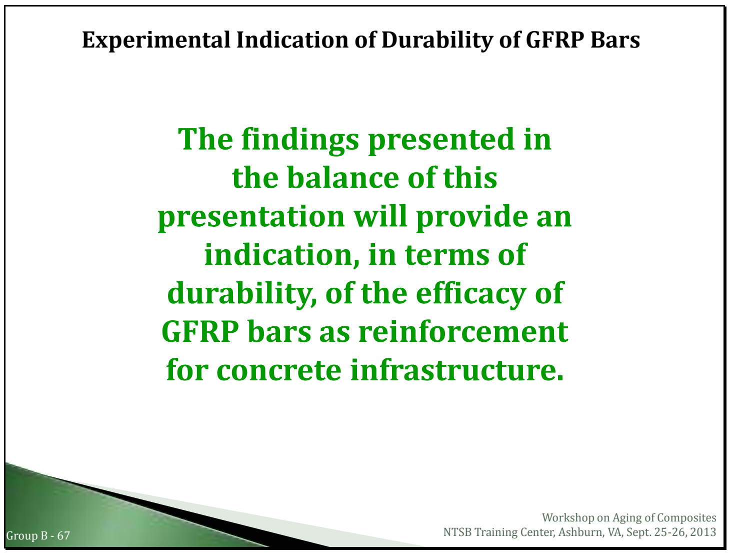

Now for a little bit of dated experimental data on the durability of GFRP bars in high pH environments. The data on the next two Group B - Slides are taken from a paper I presented at the ASCE Conference Earth & Space 2004 titled, "Time-Dependent Mechanical Property Changes of Glass Fiber-Reinforced Polymers Exposed to High pH Environments," by Francisco Aguíñiga, Timothy Bradberry and David Trejo.

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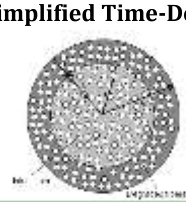
GFRP Bar Simplified Time-Dependent Degradation Model

$$x = \sqrt{2Dct} \quad (1)$$

$$\sigma_t = \left(1 - \frac{\sqrt{2Dct}}{r_0}\right)^2 \sigma_0 \quad (2)$$

$$x = \sqrt{2D\lambda t} \quad (3)$$

$$\lambda = f(c,t)$$



A primary mechanism of the degradation of a GFRP bar embedded in concrete is the diffusion of alkaline laden water through the resin matrix toward the glass fibers. The rate of this diffusion and the influence of the pore solution on the tensile strength and modulus of elasticity of the GFRP bars after 26 weeks and 50 weeks of exposure was the focus of this study.

Moisture absorption tests were performed on 150 mm capped specimens to determine absorption rates, or rates of diffusion, D, for each bar type in distilled water and the calcium hydroxide solution of pH 12 , respectively. The depth of penetration of the solution was assumed to follow Eq 1, developed by Katsuki and Uomoto (1995), where x=depth of penetration in mm, D=diffusion coefficient in mm^2 per second, c=concentration of exposure solution in moles/liter, and t=time in seconds. Using this penetration depth Katsuki and Uomoto obtained Eq 2 for computation of the residual tensile strength due to fiber degradation, where s_t, s_o, and r_0 are the tensile strength at time t in MPa, the tensile strength before exposure (i.e. time 0) in MPa, and the bar radius in mm, respectively. Katsuki and Uomoto assumed that the fibers in the region between r_0 and r_1 degrade immediately. If this model were used to predict the strength time curve of the GFRP bars in this study the bars would have no residual strength after only 1 ½ years of exposure.

But glass fibers do not immediately dissolve when exposed to water or high pH solutions. Thus, the researchers developed Eq 3 where c has been replaced by λ, a function c and t. Using the overall average diffusion coefficient obtained from the immersion tests and fitting equation 3 to the overall lowest observed tensile strengths obtained from the tension tests, an λ of 0.006 is obtained, reducing the exposure of the fibers.

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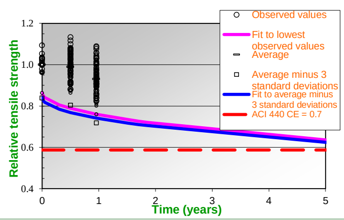
GFRP Bar Simplified Time-Dependent Degradation Model



Unstressed bars from 3 manufactures were immersed in solutions pHs 7 (distilled water) and 12 and tension tested to failure. Exposure was to three temperatures (11 C, 21 C and 35 C), the two pH levels, for two durations (26 and 50 weeks). Fifteen specimens (5 per temp) for each combination of pH and time were tested (180 total). Fifteen unexposed bars (5 per manufacturer) were also tension tested.

Experimental data and fitted and extrapolated relative strength vs. time curve is shown here (in pink) along with three calculated mean minus 3 standard deviations. The curve in blue is fitted to these statistically calculated low fractal values. This "fit to average minus 3 standard deviations" curve is extrapolated from 50 weeks to 5 years using the time-dependent degradation model. Residual/initial strength ratios at 3, 4, and 5 years are predicted to be 0.67, 0.65 and 0.63, respectively. The dashed line represents the strength ratio a designer following the ACI 440 guidelines would use and corresponds to a C_E of 0.7 multiplied by the guaranteed strength provided by the GFRP rebar manufacturer.

The blue curve indicates that the predicted residual strength would fall to the design strength in a little over 5 years. This indicates that either the ACI 440 environmental reduction factor of 0.7 needs to be lowered or the exposure conditions noted are more aggressive than is the concrete environment. This assessment assumes that the experimental data is characteristic of the durability of the bars tested in the manner tested. If instead we were to rely on the pink curve this chart indicates that the predicted residual strength would fall to the design strength in about 7 years, not much consolation.

Exposure conditions used in this study were severe and the results indicated that until data on the residual tensile strength could be obtained from GFRP samples embedded in concrete, the strength reduction factors proposed in the ACI 440 design guidelines needed to be revised. Therefore in a separate study on GFRP bars embedded in concrete specimens for 7 years, Trejo, et al reported more favorable results. Their model predicted that for a specified bar size, the probability of not meeting the ACI 440 requirement does increase with time. However, this probability decreases as the bar size increases. In particular, in 100 years #3 bars reach a 0.44 probability of not meeting the ACI 440 requirement, #5 bars reach a 0.25 probability, and #6 bars reach a 0.20 probability.

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Flashback

1 Co$t / Perceived Co$t Disadvantage
2 Lack of Performance History
~~3 Lack of Design Specifications~~
4 Education of Bridge Engineers
5 Confidence in Adhesive Bonding

There are notable advantages to FRP Composites:

BUT

~~Design Codes, Construction Specs and Inspection Methods are Needed~~

AND

Durability in Service must be proven (Jury is Still Out)

In May of 2000, John Hooks gave a presentation at the Western States Advanced Composites Workshop in Portland. He listed five challenges with regard to using FRP for bridge applications.

Then, after noting eight advantages associated with FRP Composites (High Strength, Resistant to Corrosion, Resistant to Chemicals, Toughness, Lightweight, Fatigue Resistant, Ease in Fabrication, Erection, and Short Project Delivery Time), Mr. Hooks offered these two caveats:

BUT: Design Codes, Construction Specs and Inspection Methods are Needed,

AND: Durability in Service must be proven (Jury is Still Out)

Much progress has been made over the past 13+ years in addressing Mr. Hook's five challenges and his two caveats, but only one of the challenges and it's corresponding caveat has been substantially met.

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Conclusions/Research Needs Based on Tim's Experience

- Practicing infrastructure engineers need to be educated about the appropriate and beneficial use of FRP composites.
- Uncertainties about the durability of FRP composites need to be reduced.
- Comparison of "in situ" cost between FRP composites and competing materials, such as stainless steel and ASTM A1055 rebar need to be performed and published.
- Correlate short term durability tests to long term performance of FRP rebar.
- Assess the ductility related limitations on use of FRP rebar as reinforcement in bridge elements.

Conclusions

Most structural engineers are uncomfortable designing with FRP composite materials. Questions about ductility, serviceability and durability scare them away or they just have an understandable bias toward the most tradition composite material, steel reinforced concrete. These questions and this bias should be addressed thru the education of bridge engineers.

Engineers are told that FRP composites do not rust like steel, however after a little digging they find out that the bars loose strength over time and that potentially will scare them away from considering the material. Proponents of corrosion resistant steel rebar, like Zinc and Epoxy Dual-Coated Steel Reinforcing Bars (per ASTM A1055) make claims like "it will last for more than 100 years." Whether the claim is valid or not, it is effective on those who do not feel comfortable with FRP composites.

Economic comparisons of GFRP rebar and it competitors should be on an "in situ" / as designs / as built basis preferably in terms of cost per square foot.

Research Needs

Research is needed to get a better handle on the long term durability of FRP rebar and to develop a consensus on how to correlate such durability with short term tests.

FRP rebar has enjoyed some level of acceptability as reinforcement in bridge slabs, bridge rails, and concrete pavements. The ductility of these elements is not of much concern. What other bridge elements would FRP bars be appropriate for and should/"where should" these non-ductile FRP composite rebar not be used. Perhaps, knowing the limits of FRP composites will help engineers gain a level of acceptance of this new material that currently they lack.

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Group C: Test Methods and Models

Chair: Ellen Lackey

Fire Performance of Transportation Structures Incorporating FRP

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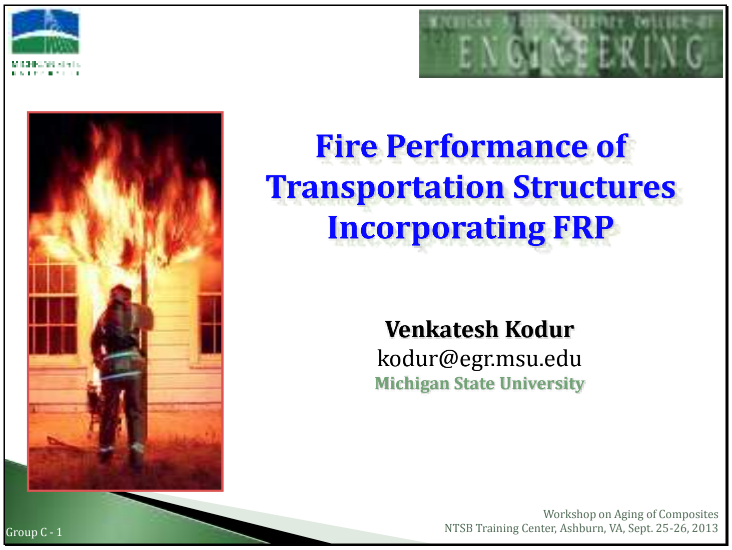

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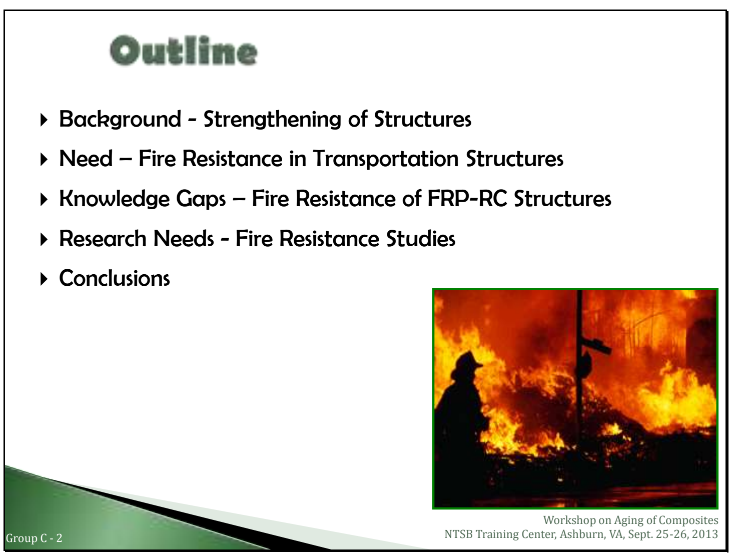

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Background

Strengthening of Structures

- World-wide Problem: Deteriorating infrastructure
  - Deterioration – RC structures
    - Corrosion of steel reinforcement
    - Aging and deteriorating of concrete
  - Emerging trend - Upgrading of infrastructure
    - Enhanced performance
      - Extreme loading events - Earthquake, Blast, Impact
    - Increased capacity
      - Heavy traffic, larger load capacity
- Solution – Retrofitting and Strengthening
  - Seismic upgrading
- Feasible Solution : Strengthening and Retrofitting
  - Increasing axial capacity of columns
  - Increasing flexural and shear capacity of beams/slabs
- Health Report Card for America's infrastructure (ASCE 2013)
  - Repairing infrastructure will cost **$3.6 trillion** over next ten years
  - Effective strategy needed for retrofitting

Deterioration in RC structures

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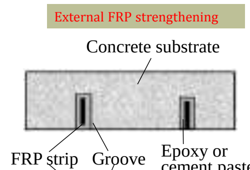
Background

Feasible Solutions – EB/NSM FRP

- Feasible technique for strengthening
- Externally bonded (EB) FRP reinforcement
  - Bonding FRP strips/plates to bottom and side faces of beams & slabs
  - Wrapping of columns with FRP sheets
- Near-surface mounted system (NSM):
  - Slots are cut into the cover of an RC member, and an FRP rebar or strip, is inserted into the slot, then filled with adhesive
- **Advantages:**
  - FRP: High strength, light-weight
  - Corrosion resistance, high durability
  - EB - Ease of application
  - NSM - Bond is generated on all faces of FRP strips, better composite action iscreated
  - NSM - Reinforcement is protected by cover concrete and thus less vulnerable to accidental impact, mechanical damage and direct fire exposure
  - NSM - Can easily be pre-stressed & also can be easily anchored to adjacent members
- **Disadvantages:**
  - Bond between concrete and FRP is not sufficient to develop full tensile strength of FRP sheets
  - Prone to the damages resulting from fire, acts of vandalism, and mechanical damage.

External FRP strengthening



NSM FRP strengthening

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Need for Fire Resistance

Fire Hazard in Bridges (Transportation Structures)

- Fires cause thousands of deaths & billions of $$ of damage yearly in built infrastructure
- Fire incidents in bridges can lead to:
  - Significant damage to structural members
  - Collapse of bridges
  - Substantial fire (property) losses
- Bridge fires are mainly caused by collision of vehicles:
  - High speed vehicle collisions can lead to burning of highly flammable hydrocarbon fuels.
- High temperature induce significant capacity degradation, due to loss of strength & stiffness.
- Proper inspection & maintenance is required before the bridge is opened to traffic.
- Shutting down a bridge for maintenance will lead to significant traffic delays and losses.

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Need for Fire Resistance

Recent Fires in Bridges - US

- I-580 freeway at MacArthur Maze interchange, Oakland, CA (April 29, 2007):
  - Fuel tanker transporting 32,500 litters of fuel overturned under the bridge.
  - Intense heat (temp. around 1100°C).
  - Strength & stiffness of steel girders deteriorated leading to large deflections.
  - Significant fire induced forces in girders & connections led to partial collapse in 22 min.
  - Losses estimated at $9 million.
- I-95 Howard Avenue Overpass, Bridgeport, CT (March 23, 2003):
  - Collision between a car & a fuel tanker transporting 50,000 liters of heating oil.
  - Fire lasted for two hours & the temp. reached about 1100°C.
  - Fire caused significant buckling of steel girders & partial collapse of steel girders.
  - Fire damage costed $11.2 million
- I-75 Expressway near Hazel Park, MI (July 15, 2009):
  - Fuel tanker carrying highly flammable fuel crashed into a truck.
  - Steel girders weakened & collapsed in 20 min.
  - The collapse of the overpass caused significant losses & major traffic delays

MacArthur Maze interchange

I-75 Expressway

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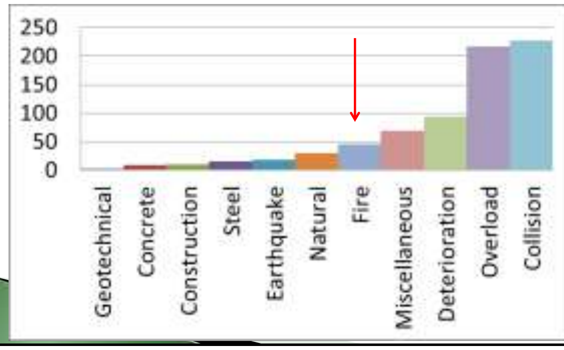
Need for Fire Resistance

Major Bridge Collapses due to Fires in USA

1876 to 2008 Survey:
- 1746 total recorded collapses;
- 1003 hydraulic failures;
- remainder shown in plot



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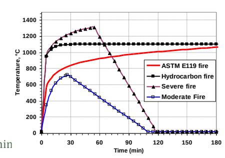
Need for Fire Resistance

Strategies for Mitigating Fire Hazard

- **Buildings –Measures to mitigate destructive impact of fire**
  - Fire Safety Provisions as per Building Codes
    - **Fire prevention, suppression & extinction**
    - **Successful evacuation of occupants**
    - **Structural fire safety – Fire resistance**

- **Bridges – No specific measures to mitigate destructive impact of fire**
  - Provision of fire resistance to structural members is key to mitigate fire hazard
    - Fire resistance **expressed as the duration during which a structural member exhibit resistance to overcome fire effects**
- **Performance of structural systems under fire conditions**
  - Fire severity
  - Material properties
  - Structural parameters and member interactions
    - Load, restraint, member interactions



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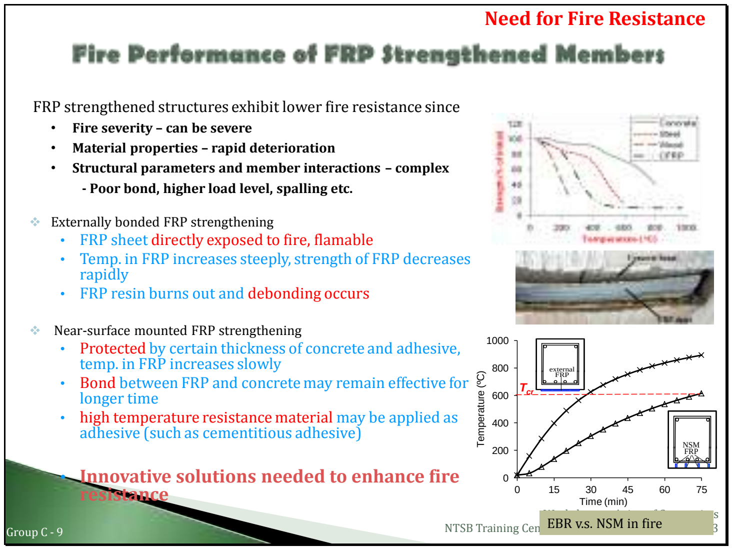

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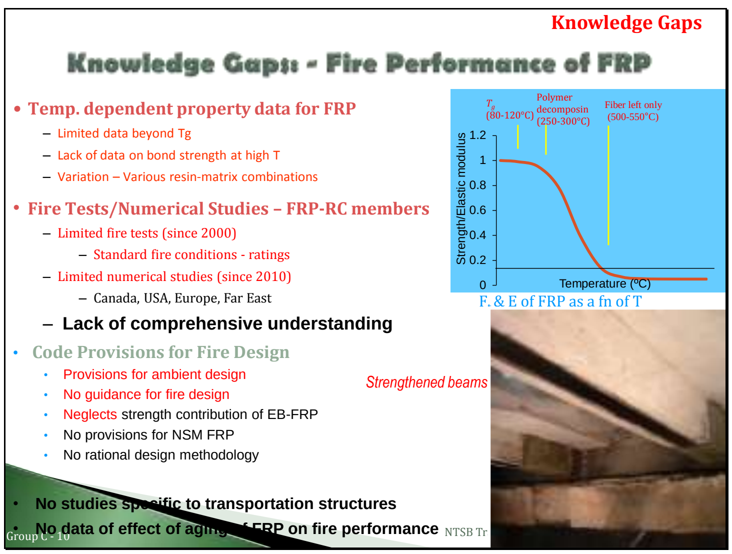

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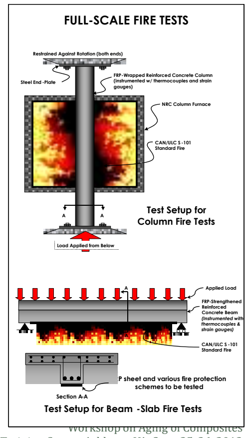
Research Needs

Fire Resistance Studies – FRP Structural Members

- Characterization of fires in transportation structures
- Material properties of FRP at el. temp.
  - aging effects
- Expt. studies on FRP-RC members
  - Columns, Beams, Slabs
    - FRP reinforcement: IR, EB, NSM
- Computer models
  - Trace fire response till failure
- Parametric studies
  - Critical factors influencing fire response
- Rational methodology for fire design
- Design guidelines
  - Fire scenarios
  - Required practical fire ratings
  - Optimum protection strategies



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Summary

Conclusions

- Fire represents a severe hazard & can lead to significant damage to transportation structures (bridges).
- There are serious fire performance problems with FRP & significant knowledge gaps on fire performance of FRP-strengthened RC structures.
- FRP is a combustible material and experiences significant loss of properties at relatively low temperatures as compared to concrete and steel. Further, bond strength and modulus of NSM FRP system decrease rapidly with temp., and only 20% is retained at 200°C.
- Provision of fire resistance to structural members is key for enhancing fire safety of transportation structures incorporating FRP.
- Through fire resistance experiments & advance calculation models it is possible to develop unique strategies for enhancing fire performance of transportation structures incorporating FRP.

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Advanced Test Methods for Evaluating the Durability Performance of FRP Materials

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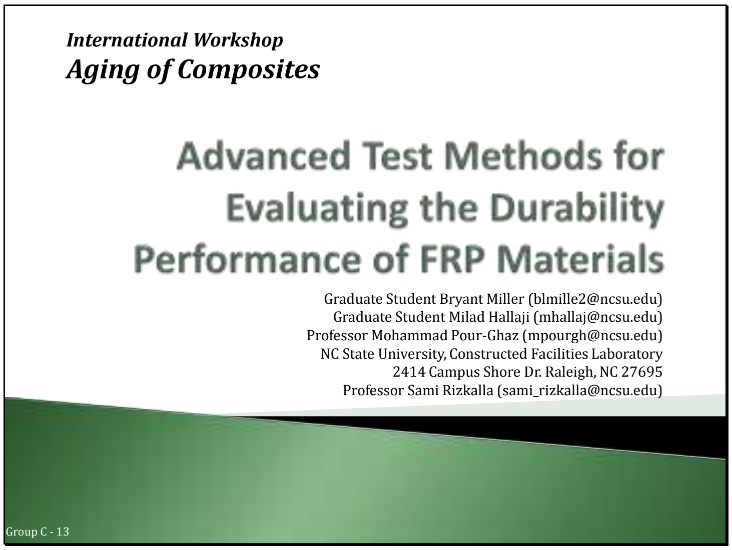

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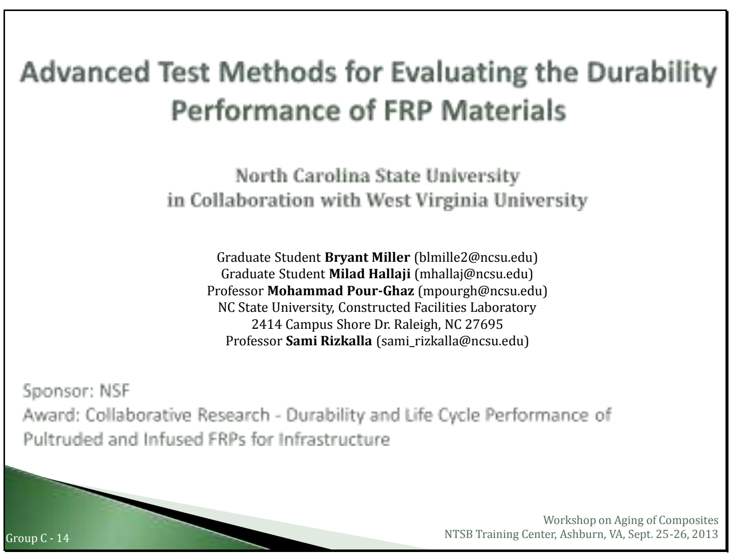

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Summary

This presentation focuses on aging and durability issues of commercially available pultruded glass composites, consisting of either a vinylester or polyester matrix. During their service life, these FRP materials are subjected to a combination of mechanical and environmental loadings that may degrade their mechanical properties. Previous studies have investigated the effects of various environmental conditionings such as different types of solutions, temperature, accelerated aging, and loading conditions. However, data on the synergistic effect of all aggressive agents, temperature, and mechanical loading are scarce. There is a need to fundamentally understand the nonlinear coupling of environmental and mechanical loadings. Future research needs to address and study the synergistic effects of various conditionings, establish mechanistic models for degradation mechanisms, develop fundamental test methods to quantify damage in FRP materials, and determine the life cycle performance of the composites.

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Overview of critical areas of durability

- Accelerated Aging
  - Understanding the mechanism changes due to accelerated aging
- Effects due to Solutions
  - Chemical/physical effect of solutions
- Freeze-Thaw Conditioning
  - Rate dependence
- Synergistic Effects
  - Understanding the effect of cracks on acceleration of degradation
  - Methods to model the effect of cracks and discontinuities
  - Interface engineering
  - Multi-physics multi-scale modeling to understand nonlinear coupling of mechanical and environmental loadings
- Fundamental Test Method
  - Rapid and mechanistic method
  - Field and lab

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Synergistic conditioning of samples

Conditioning Parameters

Accelerated aging at 60°C is being performed on specimens, and the effect of solution (freshwater and saltwater) is being studied under sustained loading (0, 10, 20, or 30 percent of ultimate tensile stress). Mechanical tests are being performed to understand the nonlinear coupling effects of these parameters. Advanced test methods, such as acoustic emission, are being utilized to understand the effect of accelerated aging on interfaces within the FRP.

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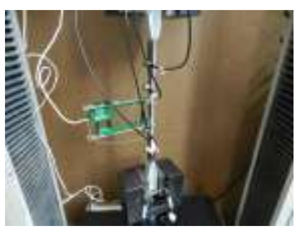
Methods of assessing durability issues: Acoustic emission

Acoustic emission testing is being performed on FRP specimens with the goal of using this test method to understand the effect of aging, mechanical loading, and exposure to aggressive agents on the failure of different constituents of the composite. Using waveform analysis, this test method can be used to potentially differentiate between matrix cracking, fiber cracking, and interface cracking. It is hypothesized that degradation of different phases will result in frequency shifts and therefore acoustic emission might provide a fundamental and rapid method for quantifying damage due to aging.



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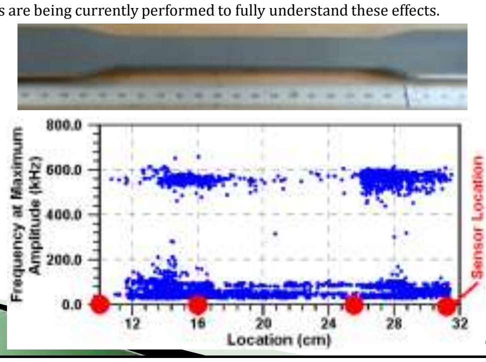
Methods of assessing durability issues: Preliminary acoustic emission results

Preliminary results show that there are two/three distinct frequency ranges emitted from FRP during tensile loading. It is postulated that matrix cracking corresponds to the lower frequency band and occurs more distributed along the dog-bone gage length and tapered regions. It is also postulated that fiber breakage corresponds to the higher frequency band and occurs locally at the tapered region where the sample ultimately fails. Some preliminary results are shown below. More analyses are being currently performed to fully understand these effects.



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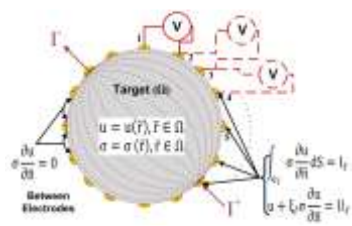
Methods of assessing durability issues: Electrical Resistance Tomography (ERT)

ERT is a model-informed imaging modality that reconstructs spatial conductivity (σ) (or alternatively resistivity) distribution of an object. This is accomplished by physically measuring the electrode potentials at the boundaries of the object under the influence of an applied current. The current is applied (or injected) between different pairs of boundary electrodes and the resulting electrical potential differences across the remaining pairs of electrodes are measured. This test method is being investigated as a potential test method for damage detection in CFRP materials. In this method inverse problems are utilized to reconstruct the conductivity distribution within materials.



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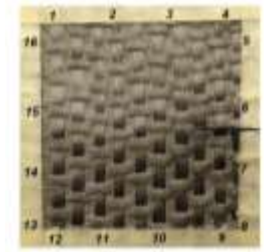
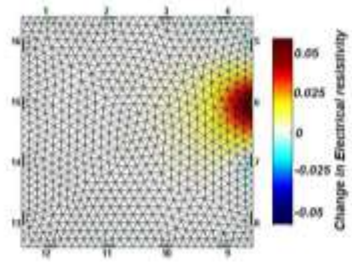
Methods of assessing durability issues: Electrical Resistance Tomography (ERT)

Preliminary results indicate that ERT can be used for damage detection in CFRP materials. Advanced computational and numerical methods for ERT currently being developed at NC State to extend this method for damage detection in large geometries and to account for the anisotropic conductivity distribution. Different fiber architecture are being used to fully realize the feasibility of this method for damage detection in CFRP materials.





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Areas in need of future research

- Study the synergistic effects of mechanical and environmental loadings
- Develop multi-physics multi-scale models that can model the nonlinear coupling between mechanical and environmental loadings
- Quantify the behavior of FRP composite constituents at both the micro- and macro-scales
- Establish fundamental understanding of the deterioration mechanisms and understand how acceleration of aging affects the mechanisms of degradation
  - This will help develop better acceleration methods and the results of accelerated test methods can be better correlated to naturally aged samples
- Develop models for service life prediction of FRP materials
- Develop fundamental test methods for durability performance characterization
- Life cycle assessment (LCA) of FRP so that sustainability of FRP materials and structures can be fundamentally quantified
- Development of exposure sites

Determining Characteristic Values of Pultruded Composites Exposed to Environmental Conditioning for use with the LRFD Standard

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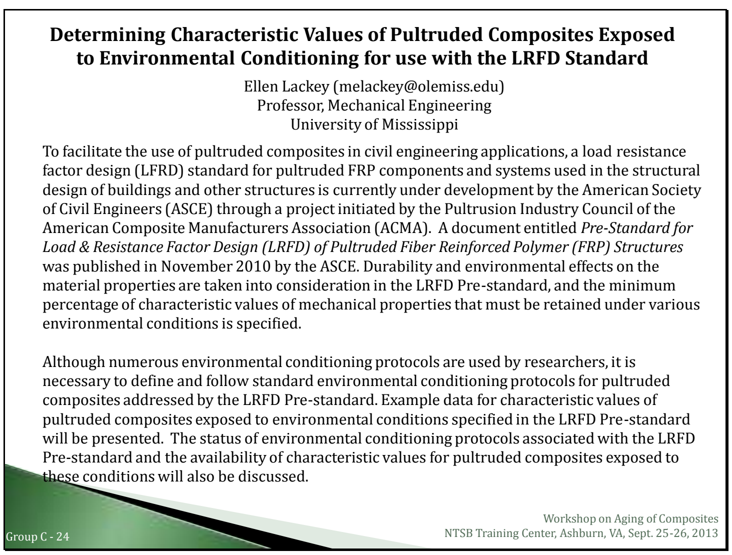

The LRFD Pre-standard provides guidelines for various aspects associated with the use of pultruded composites for structural design. For example, guidelines are provided for the constituent materials used for the manufacture of pultruded FRP components and systems used in the structural design of buildings and other structures. In addition to requirements for constituent materials used in the manufacture of the pultruded composites, minimum physical and mechanical property values which the pultruded composites must meet are specified.

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Requirements for Durability and Environmental Effects Provided in Section 1.3.4 of the LRFD Pre-standard for Pultruded Composites[1]

Unless the glass transition temperature determined in accordance with ASTM D4065 and the tensile strength of the composite in the longitudinal and transverse directions determined in accordance with ASTM D638, can be shown to retain at least 85% of their characteristic values after conditioning in the environments listed below, the nominal strength and stiffness shall be reduced in accordance with Section 2.4.4(a). Materials that cannot retain at least 15% of their characteristic values after conditioning in the environments listed below shall not be permitted.[1]

Water: Samples shall be immersed in distilled water having a temperature of 100 ± 3°F (38 ± 2°C) and tested after 1,000 hours of exposure.

[1]*Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures (Final)*, ASCE, November 9, 2010.

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Requirements for Durability and Environmental Effects Provided in Section 1.3.4 of the LRFD Pre-standard for Pultruded Composites (Cont)

Alternating ultraviolet light and condensating humidity: Samples shall be exposed according to Cycle No. 1 (0.89W/m^2/mm, 8 hours UV at 60ºC, 4 hours condensation at 50ºC) using UVA*340 lamps in an apparatus meeting the requirements of ASTM G154. Samples shall be tested within two hours after removal from the apparatus.

Alkali: Where required, the sample shall be immersed in a saturated solution of calcium hydroxide (pH ≥ 11) at ambient temperature of 73 ± 3°F (23 ± 2°C) for 1000 hours prior to testing. The pH level shall be monitored and the solution shall be maintained as needed.

Freeze-thaw: Composite panels or coupons shall be exposed to 100 repeated cycles of freezing and thawing in an apparatus meeting the requirements of ASTM C666."

Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures (Final), ASCE, November 9, 2010.

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Adjustments to Reference Strength Provided in Section 2.4.4 of the LRFD Pre-standard for Pultruded Composites

2.4.4 Adjustments to Reference Strength

Except where stipulated in other sections of this Standard, the nominal strength shall be determined by multiplying the reference strength by the adjustment factors set forth in Table 2.4-1.

(a) Adjustment factors for end-use. For sustained end-use conditions that differ from the reference conditions set forth in Sec. 2.4.2, adjustment factors shall be determined by tests stipulated by the Engineer of Record. In the absence of such tests, it is permitted to utilize the adjustment factors in this section.

C_M = moisture condition factor in Table 2.4-1 to account for sustained in-service moisture;

C_T = temperature factor in Table 2.4-1 to account for a sustained in-service temperature higher than 90°F (32°C) but less than T_g − 40°F. For sustained temperatures in excess of 140°F (60°C), C_T shall be determined from tests stipulated by the Engineer of Record.

Table 2.4-1 Adjustment factors for end use conditions

Reference Property	Moisture C_M	Temperature (°F) C_T for $(90 < T \le 140)$
Vinyl ester material		
Strength	0.85	1.7 − 0.008T
Elastic modulus	0.95	1.5 − 0.006T
Polyester material		
Strength	0.80	1.9 − 0.010T
Elastic modulus	0.90	1.7 − 0.008T

C_{CH} = chemical environmental factor (high alkalinity, acidity), determined from interpolation or extrapolation of the results of ASTM C581 tests performed on the laminate exposed to the exposure chemical environment for a period of 1,000 hours, or as stipulated by the Engineer of Record.

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- Conditioning protocols intended specifically to address the requirements for the LRFD Pre-standard do not currently exist
- These protocols are needed to allow uniform comparison of materials under the LRFD standard
- 100°F Water Immersion and Freeze Thaw Conditioning protocols to specifically address the conditioning requirements from the LRFD Pre-standard are currently under development by ASTM D20.18.02
- Alkali/other corrosion conditioning requirements are under discussion and may have protocols developed to address these

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Examples of Details TBD for 100°F Water Immersion Conditioning Protocol

Water: Samples shall be immersed in distilled water having a temperature of 100 ± 3°F (38 ± 2°C) and tested after 1,000 hours of exposure.

- Coated or non-coated cut surfaces for conditioned samples
- Machining of samples before or after exposure
- Sampling locations
- Allowable time window from removal of material from conditioning bath until samples are tested
- Mechanical property test method to be used to evaluate environmental effects
- Stagnant or circulated water

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Examples of Details TBD for 100°F Water Immersion Conditioning Protocol

- Coated or **non-coated** cut surfaces for conditioned samples
- Machining of samples **before** or after exposure
- Sampling locations **(random but known)**
- Allowable time window from removal of material from conditioning bath until samples are tested **(4 hours)**
- Mechanical property test method to be used to evaluate environmental effects **(D638 tension testing as per LRFD Pre-standard)**
- Stagnant or **circulated** water

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Example Data - Comparison of Average Values and Characteristic Values (ASTM D7290) of Tensile Strength (ASTM D638) Data for As-Pultruded and 100°F Distilled Water Conditioned Pultruded Composites

Material	As Received – No Environmental Conditioning			Conditioned in 100°F Distilled Water Immersion Bath for 1000 hours		
	Characteristic Value (ksi)	Average (ksi)	St. Dev. (ksi)	Characteristic Value (ksi)	Average (ksi)	St. Dev. (ksi)
E-glass/ Polyester Pultruded Composite Plate	34.9	45.6	3.9	28.2	42.5	5.8
E-glass/ Vinyl Ester Pultruded Composite Plate	33.4	43.3	3.7	29.8	36.2	2.0

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Future Research Needs/Directions for this Area

- 100°F Water Immersion and Freeze Thaw Conditioning protocols to specifically address the conditioning requirements from the LRFD Pre-standard are currently under development by ASTM D20.18.02 – Continued development of these and other protocols are needed to support the LRFD standard for pultruded composites

- Alkali/other corrosion conditioning requirements are under discussion and may have protocols developed to address these – Additional protocols will be needed or existing protocols may need to be modified as new developments are incorporated into existing design standards

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Accelerated Testing Methodology for Long-Term Life Prediction of Polymer Composites

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International Workshop
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Accelerated Testing Methodology for Long-Term Life Prediction of Polymer Composites

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Accelerated Testing Methodology for Long-Term Life Prediction of Polymer Composites

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Summary

We have proposed a general and rigorous advanced accelerated testing methodology (ATM-2) which can be applied to the life prediction of CFRP exposed to an actual load and environment history based on the three conditions. One of these conditions is the fact that the time and temperature dependence on the strength of CFRP is controlled by the viscoelasticity of matrix resin. The tensile and compressive static strengths in the longitudinal and transverse directions of two kinds of unidirectional CFRP under wet condition are evaluated using ATM-2. The applicability of ATM-2 and the effect of water absorption on time and temperature dependence of these static strengths are demonstrated.

Acknowledgements

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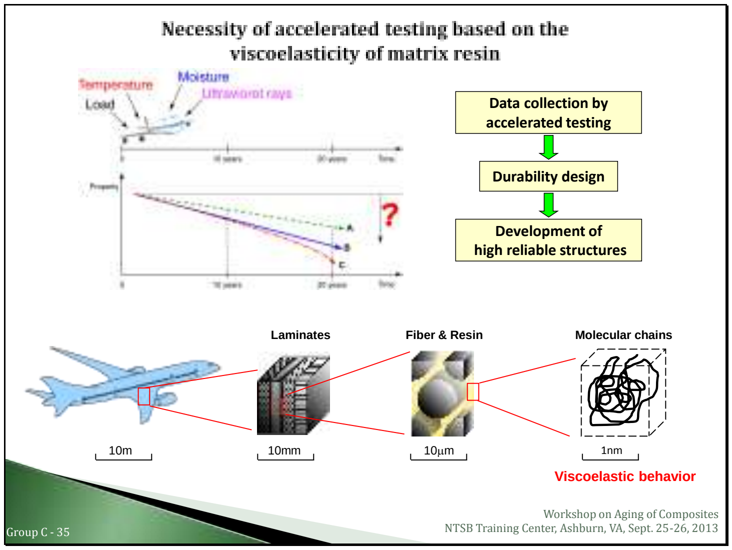

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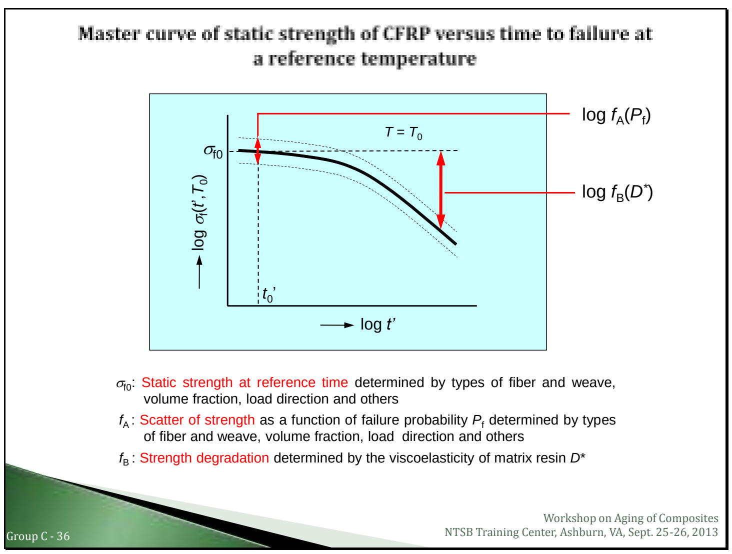

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Formulation of static strength of CFRP based on ATM

The master curve of static strength of CFRP can be shown by the following equation based on conditions of A and B.

$$\log\sigma_f(P_f,t',T_0)=\log\sigma_{f0}(t'_0,T_0)+\frac{1}{\alpha}\log[-\ln(1-P_f)]-n_r\log\left[\frac{D^*(t',T_0)}{D_c(t'_0,T_0)}\right]$$

The first term shows the scale parameter for static strength at reference temperature T_0 and reduced reference time t_0'.

The second term shows Weibull distribution as a function of failure probability P_f. a is shape parameter for static strength. (Condition A)

The third term shows the variation of static strength by the viscoelastic compliance D^* of matrix resin which is determined by the creep compliance D_c of matrix resin and temperature and load histories of CFRP. n_r is material parameter determined by failure mechanism. (Condition B)

Condition A: The failure probability is independent of temperature and load histories.

Condition B: The time and temperature dependence of strength of CFRP is controlled by the viscoelasticity of matrix resin. Therefore, the time-temperature superposition principle for the viscoelasticity of matrix resin holds for the strength of CFRP.

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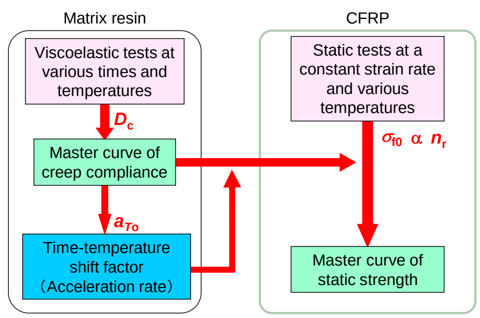
Procedure of accelerated testing



1st step Determination of a_{To} and D_c for matrix resin
2nd step Determination of σ_{f0}, α, n_r for CFRP

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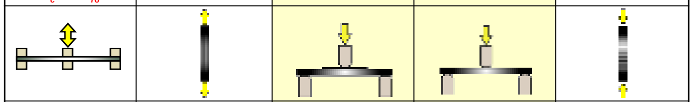
Configuration of test specimens

Viscoelastic modulus and TTSF D_c and a_{T_0}	Longitudinal tensile strength X	Longitudinal compressive strength X'	Transverse tensile strength Y	Transverse compressive strength Y'
UD 90° Dual cantilever bending	UD 0° Tension	UD 0° Bending (with cushion)	UD 90° Bending	UD 90° Compression



Unidirectional CFRP (T300/EP)

Specimen	Thickness	Fiber direction	Curing and drying in air	Water absorption in water	Water content
Dry	1mm & 2mm	0° & 90°	135°Cx2h + 160°Cx2h + 110°Cx50h	-	0 wt%
Wet	1mm	0°	135°Cx2h + 160°Cx2h + 110°Cx50h	95°Cx121h	1.9 wt%
	2mm	0°		95°Cx144h	
		90°		95°Cx121h	

Unidirectional CFRP (T700/VE)

Specimen	Thickness	Fiber direction	Curing and drying in air	Water absorption in water	Water content
Dry	1mm & 2mm	0° & 90°	25°Cx24h + 150°Cx2h	-	0 wt%
Wet	1mm	0°	25°Cx24h + 150°Cx2h	95°Cx25h	0.7 wt%
	2mm	0°			0.5 wt%
		90°			0.5 wt%

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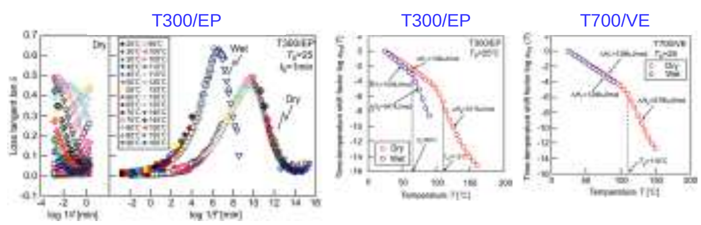
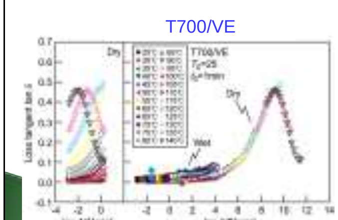
Determination of TTSF from tan δ in transverse direction of unidirectional CFRP





Time-temperature shift factor:

$$\log a_{T_0}(T) = \frac{\Delta H_1}{2.303G}\left(\frac{1}{T} - \frac{1}{T_0}\right) \mathrm{H}(T_g - T) + \left[\frac{\Delta H_1}{2.303G}\left(\frac{1}{T_g} - \frac{1}{T_0}\right) + \frac{\Delta H_2}{2.303G}\left(\frac{1}{T} - \frac{1}{T_g}\right)\right](1 - \mathrm{H}(T_g - T))$$

a_{T_0}: Time-temperature shift factor,
G: Gas constant,
ΔH: Activation energy, T: Temperature, T_0: Reference temperature,
T_g: Glass transition temperature, H: Heaviside step function

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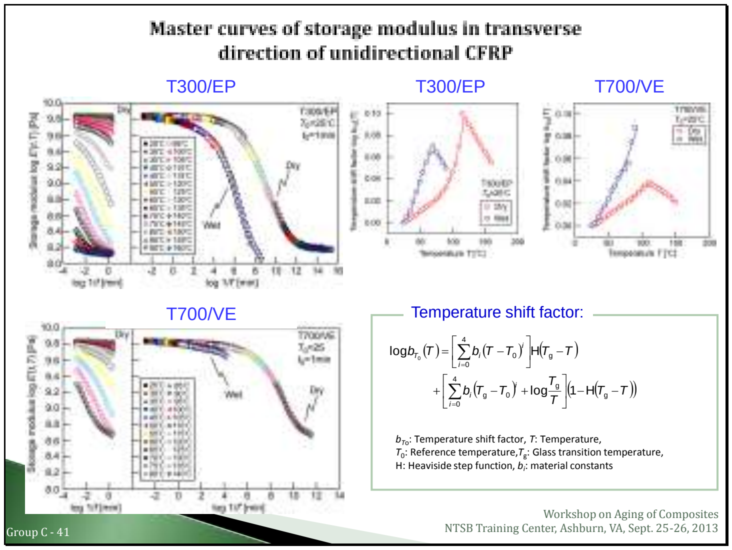

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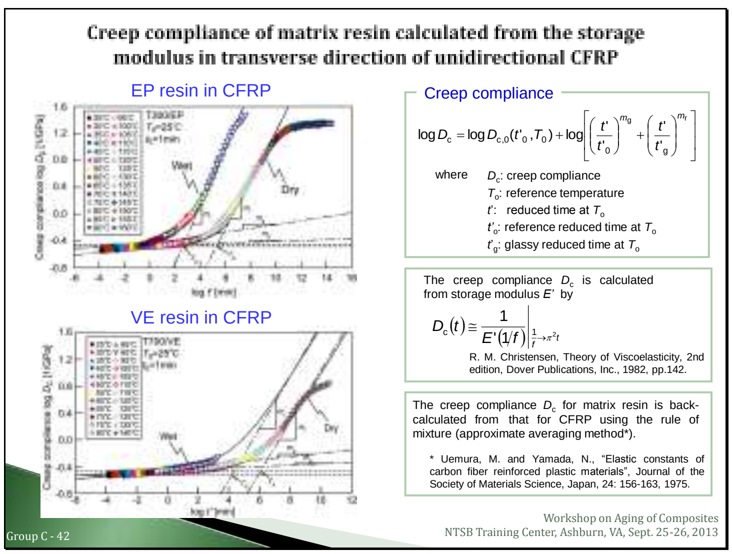

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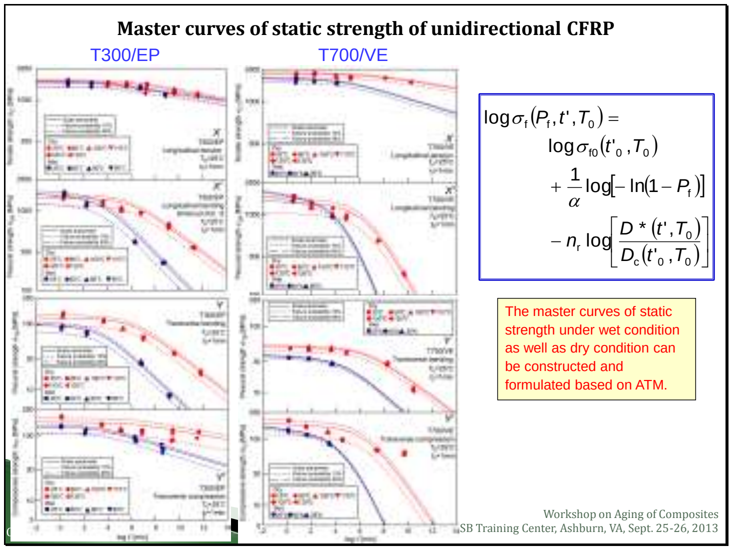

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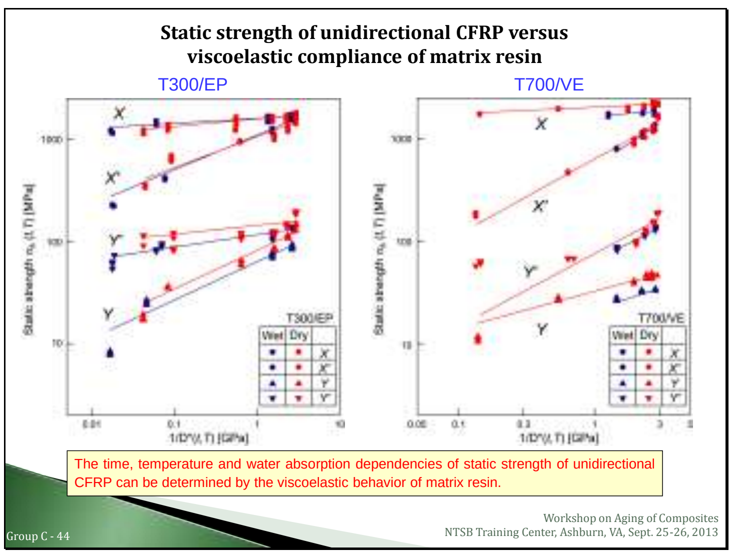

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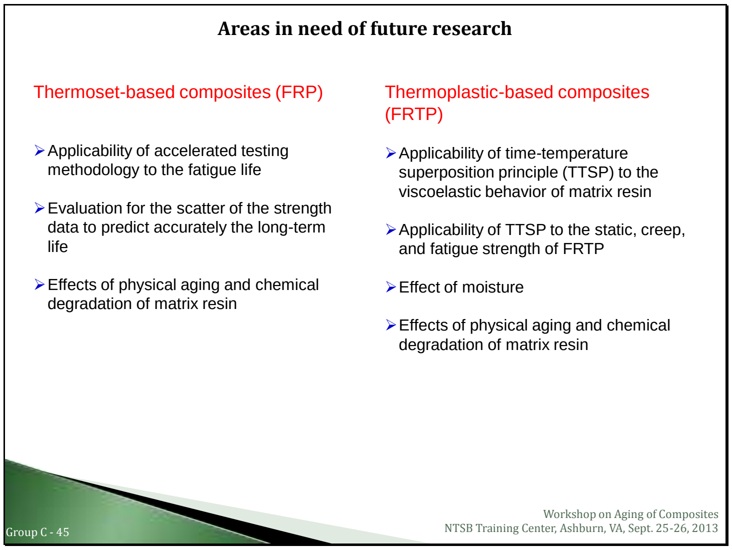

Compressive Behaviour of Composites: Laboratory-based accelerated ageing

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Keywords: Composite laminates; Compressive strength; Shear strength; Environmental degradation; Hygro-thermal effects; Open hole compression; Fibre microbuckling.

References

1. Soutis, C. "Compressive strength of unidirectional composites: measurement and prediction". ASTM-STP1242, 13, (1997), 168-176.
2. Soutis, C. "Modelling the open hole compressive strength of composite laminates tested in hot-wet conditions". Plastics, Rubber and Composites, 38(2-4), (2009), 55-60.
3. Jumahat, A., Soutis, C. and Hodzic, A. "A graphical method predicting the compressive strength of toughened unidirectionalcomposite laminates". Applied Composite Materials, 18(1), (2010), 65-83.

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ABSTRACT

The talk will present recent experimental and analytical results on the compressive and in-plane shear response of T800/924C carbon fibre-epoxy composite laminates (currently available for aerospace structural applications) exposed to hot-wet environments. The weight gains, maximum moisture contents and diffusion coefficients of unidirectional and various multidirectional laminates immersed in boiling water (accelerated ageing) were measured in earlier work [1-3] and briefly will be reported here. Data will also be presented on the effects of moisture and temperature on the uniaxial compressive strength/failure mode of unidirectional laminates and multidirectional plates with an open hole. It will be shown that the failure in the hot-wet specimens always occurs as a result of out-of-plane microbuckling of the 0^0 plies. This is attributed to the reduction in matrix strength properties and weakening of the ply interface arising from elevated temperatures and environmental conditioning. Test results will be compared to theoretical predictions made by the Budiansky fibre microbuckling model and the Soutis-Fleck cohesive zone model for the open hole (notched) compressive (OHC) strength.

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Keywords: Composite laminates; Compressive strength; Shear strength; Environmental degradation; Hygro-thermal effects; Open hole compression; Fibre microbuckling.

References

1. Soutis, C. "Compressive strength of unidirectional composites: measurement and prediction". ASTM-STP1242, 13, (1997), 168-176.
2. Soutis, C. "Modelling the open hole compressive strength of composite laminates tested in hot-wet conditions". Plastics, Rubber and Composites, 38(2-4), (2009), 55-60.
3. Jumahat, A., Soutis, C. and Hodzic, A. "A graphical method predicting the compressive strength of toughened unidirectionalcomposite laminates". Applied Composite Materials, 18(1), (2010), 65-83.

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Outline

- Background
  - Damage mechanisms in composites
  - Fibre microbuckling
  - Fibre kinking
- Moisture absorption
  - Shear
  - Compression, UD
  - Open hole compression
- Damage Zone Modelling
- Concluding remarks

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What are the benefits?

- Weight saving compared to aluminium alloys
- High strength and stiffness (3 to 6x higher than Al-Zn-Mg alloy)
- Tailored directional mechanical properties- complex shapes and contours easily accomplished
- Reduced part count over metallic equivalent
- Reduced machining
- Non-corroding in aggressive environments
- Excellent fatigue resistance
- Potential for embedded functionality (damage sensing etc)

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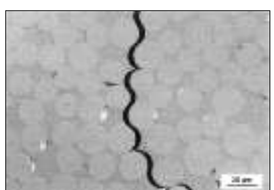
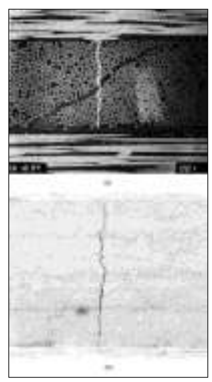
Damage Mechanisms under Tension

- **Matrix Cracking** causes degradation of the overall stiffness properties of the laminate
- Triggers development of other damage modes, delamination and fibre breakage
- Accelerates moisture absorption





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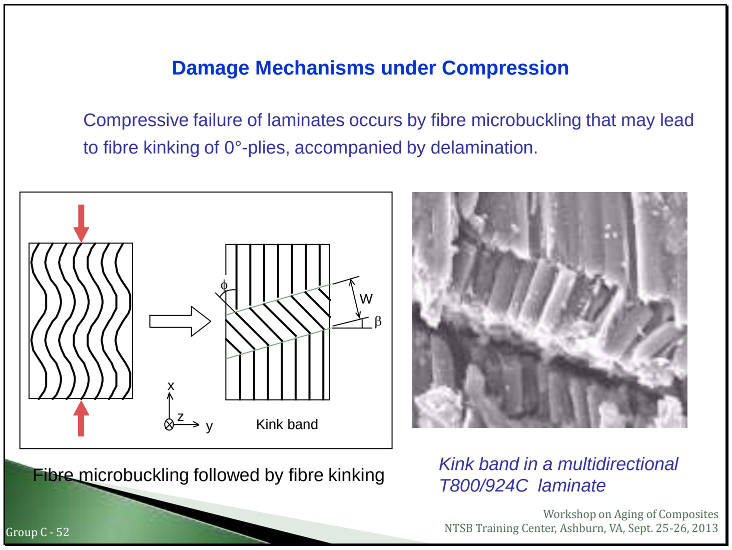

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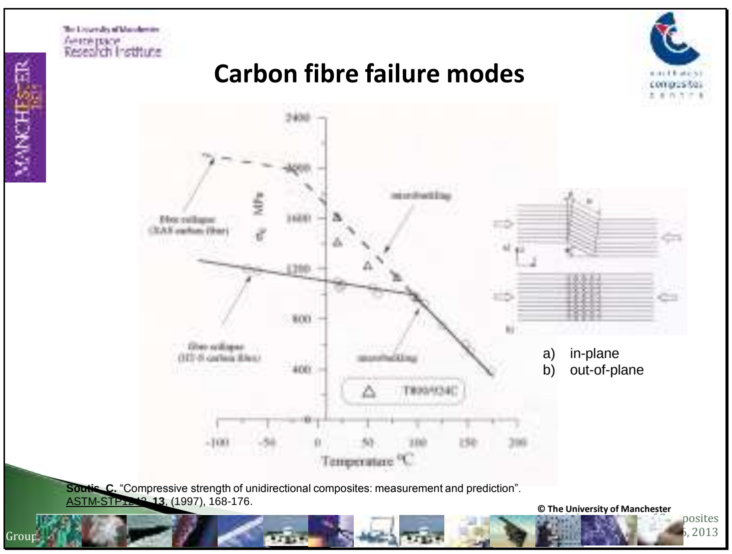

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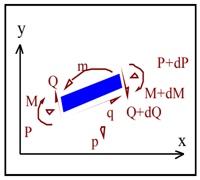
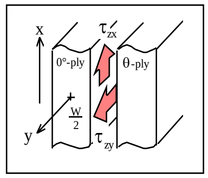
Modelling of fibre microbuckling





$$v_0(x) = V_0 \cdot \sin\left(\frac{\pi x}{\lambda}\right)$$

$$p(s) = d_{fibre}\left(\tau_{zx}\,\vec{n}\cdot\vec{i} + \tau_{zy}\,\vec{n}\cdot\vec{j}\right)$$

Equilibrium equation:

$$E_f I \frac{d^4(v-v_0)}{dx^4} + \frac{A_f \sigma_{0°-ply}}{V_f}\cdot\frac{d^2 v}{dx^2} - 2 d_f \left\{\left[\frac{d\tau_{zy}}{dy}\right]_{\frac{w}{2}}\right\}\cdot v - A_f G\left(\frac{d(v-v_0)}{dx}\right)\cdot\frac{d^2(v-v_0)}{dx^2} = 0$$

Non-linear differential equation that gives the compressive stress σ_0 in the 0°-ply in terms of fibre maximum buckling amplitude v and fibre waviness v_0

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Moisture absorption

- The epoxy resin absorbs moisture while the fibres do not.
- Most of the evidence in the literature suggests that water is absorbed by a bulk diffusion mechanism in the resin
- For flat plates the rate of moisture absorption through the thickness direction can be described by Fick's second law

$$M(t) = M_o + (M_\infty - M_o)\frac{4}{h}\sqrt{\frac{Dt}{\pi}}$$

Equilibrium moisture content M_∞ =1.42%

Table 1. Coefficient of moisture diffusion for T800/924C

Diffusivity mm²/s	$[0_8]_s$	$[(\pm 45/0_2)_3]_s$
D_∞	8.42x10^{-7}	9.3x10^{-7}

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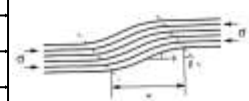
UD properties

Compressive & Shear strength properties of T800/924C unidirectional laminates

Test Temperature °C	Compressive Strength MPa	Young's Modulus* GPa	Shear Strength MPa	Shear Yield Stress MPa	Shear Modulus GPa
20-dry	**1415** (1411)	160	110	40	6.0
20-wet	1060 (1040)	-	(89)	(29.5)	(5.4)
50-dry	1230 (1235)	155	105	35	5.8
50-wet	930 (917)	-	(78)	(26)	(5.4)
80-dry	1137 (1129)	149	98	32	5.4
80-wet	828 (829)	-	(69)	(23)	(4.9)
100-dry	973 (953)	136	90	28	4.9
100-wet	**654** (653)	-	(54)	(18.5)	(4.5)

$$\sigma = \frac{\tau_y \left[1 + \left(\frac{\sigma_{T_y}}{\tau_y} \right)^2 \tan^2 \beta \right]^{\frac{1}{2}}}{\phi_0 + \phi}$$



( ) Theoretical predictions ϕ_0=1.75° β= 15°

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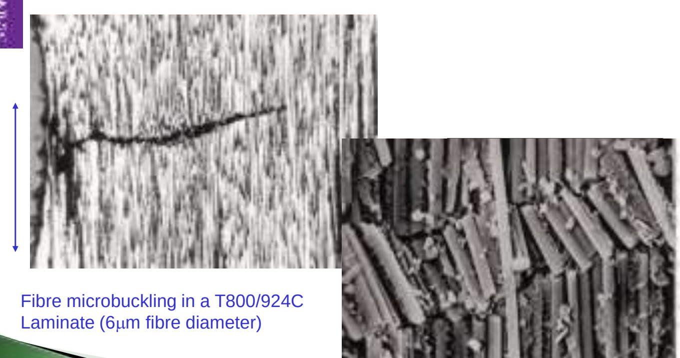
The University of Manchester Aerospace Research Institute

Compressive failure of a CFRP plate with a hole



Fibre microbuckling in a T800/924C Laminate (6μm fibre diameter)

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Group ... posites ..., 2013

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Open Hole Compression

Compressive strength results for T800/924C laminates with a 5mm hole.

Test temp C	Exp OHC MPa $[(\pm 45,0_2)_3]_s$	Predicted OHC MPa $[(\pm 45,0_2)_3]_s$	Exp OHC MPa $[(90_2,0_2)_3]_s$	Predicted OHC MPa $[(90_2,0_2)_3]_s$
20-Dry	451.75	342.0	351.65	290.9
20-Wet	402.00	293.6	-	232.0
50-Dry	421.50	309.6	324.67	259.7
50-Wet	357.50	259.0	-	211.2
80-Dry	371.50	293.9	291.37	244.4
80-Wet	325.00	241.2	-	195.1
100-Dry	-	265.5		217.5
100-Wet	282.00	208.3	-	167.6

$$G_c = 2\int_0^{v_c} \sigma(v)\, dv = \sigma_{un} v_c$$

$$2v_c = w = \frac{\pi d_f}{4}\left(\frac{V_f E_f}{2\tau_y}\right)^{\frac{1}{3}} \approx 0.62\, d_f \left(\frac{v_f E_f}{\tau_y}\right)^{0.33}$$

For the T800/924C $[(\pm 45,0_2)_3]_s$

$2v_c$=56 mm, G_C=22.74 kJ/m2 20-Dry conditions

* Longitudinal UD compressive strength, shear yield strength and $G_C(\tau_y)$ are the input data for the predicted OHC results

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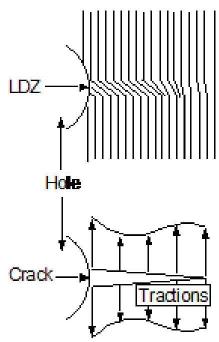
Damage Zone Modelling



- The DZ is treated as an equivalent crack
- The traction distribution describes the load transfer characteristics of the damage zone
- Damage propagation is controlled by *traction law* and applied loading
- Three experimentally measured phenomena are predicted with a consistent physically-based model: DZ growth, critical length, ultimate failure load

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Concluding Remarks

- Composite Materials properties are excellent
  - But still challenges to be met, especially when tested in hot-wet environments
- Fickian diffusion is sufficiently accurate for the cases examined
- The strength properties of specimens tested in hot-wet conditions were substantially reduced
- In hot-wet environments final failure always occurred due to out-of-plane fibre microbuckling.

Priority Topics on composites:

- Joining and Joints, NDT, Repair, Recycling/Disposal

Jumahat, A., Soutis, C. and Hodzic, A. "A graphical method predicting the compressive strength of toughened unidirectional composite laminates". Applied Composite Materials, **18**(1), (2010), 65-83.

Soutis, C. "Modelling the open hole compressive strength of composite laminates tested in hot-wet conditions". Plastics, Rubber and Composites, **38**(2/3/4), (2009), 55-60.

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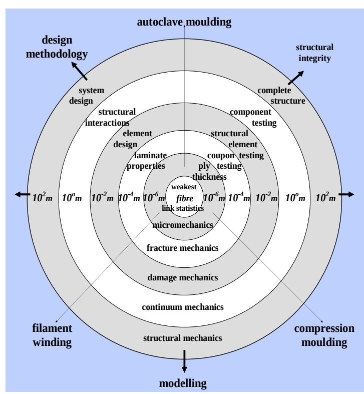
Composites Design



Soutis & PWR Beaumont
Multi-scale modelling

- Confidence in failure criteria is low, need to include manufacturing defects

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FDOT's Experience with Material Durability and its Application to Polymers

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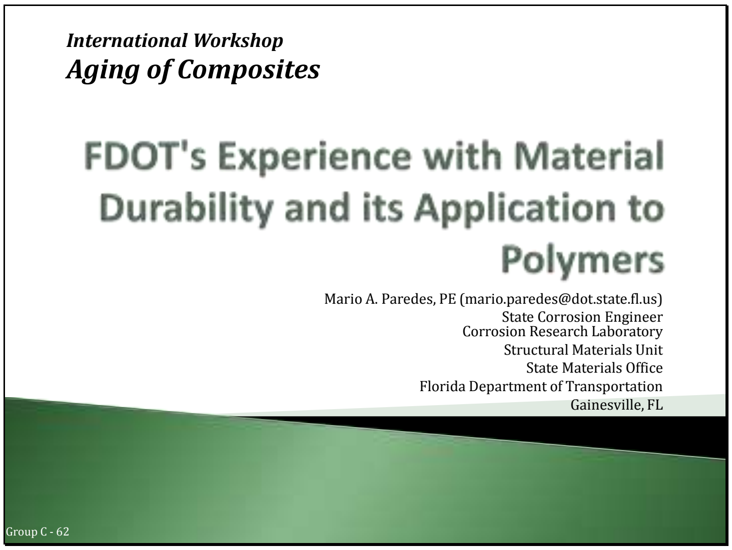

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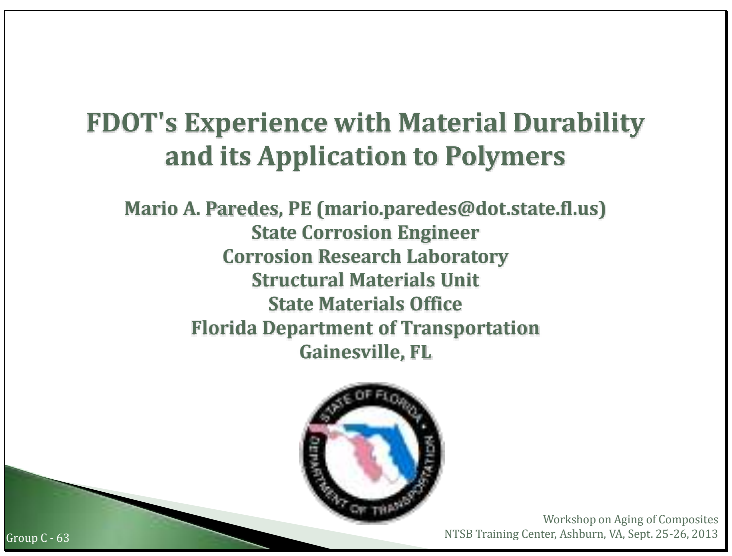

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Definitions

➢ **Service Life:** As per SHRP2 R19A, the time duration during which the bridge element, component, subsystem, or system provides the desired level of performance or functionality, with any required level of repair and/or maintenance.

➢ **Target Design Service Life:** The time duration during which the bridge element, component, subsystem, and system is expected to provide the desired function with a specified level of maintenance established at the design or retrofit stage.

➢ **Design Life:** The period of time on which the statistical derivation of transient loads is based: 75 years for the current version of AASHTO LRFD Bridge Design Specifications (2012).

FDOT is one of a few DOT with a section dedicated to service life.

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Responsibilities

- Ensure materials can achieve required service life
- Corrosion of Rebar embedded in concrete
- Metal pipe
- Plastic pipe – PVC, HDPE, PP
- ADA Mats
- Composite Rebar
- Composites in general – Fender piles, signs and posts

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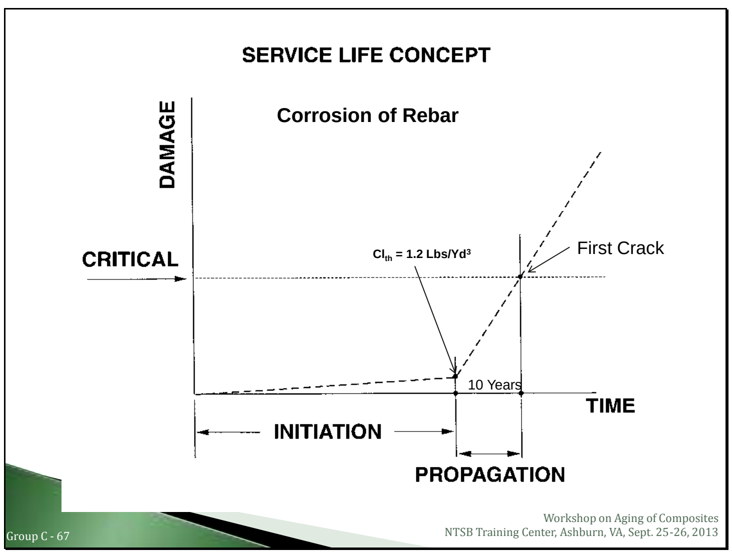

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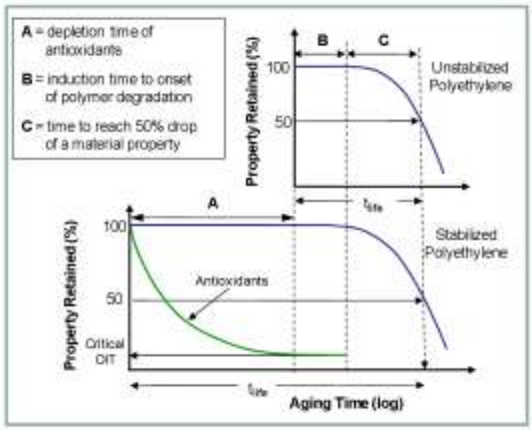
SERVICE LIFE CONCEPT – Oxidation HDPE



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Research

All work focuses on developing testing program for product approval

Completed
•HDPE Service Life – Grace Hsuan, Drexel University

In progress
•FRP reinforcement – Brahim Benmokrane, Sherbrooke University
•UV of polymers – Grace Hsuan, Drexel University

Future
•FRP resin degradation – Future project
•FRP fiber degradation – Future project
•Polymer Hydrolysis degradation – Future project
•Polymer Oxidation Degradation – Future project

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Group D: Degradation and Life Prediction Models

Chair: Charles Bakis

Aging Mechanisms in Polymers and their Composites: Molecular-level Responses

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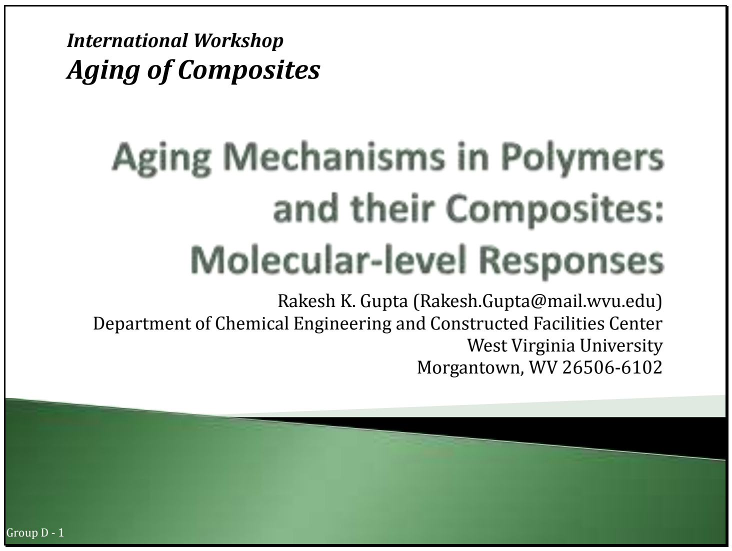
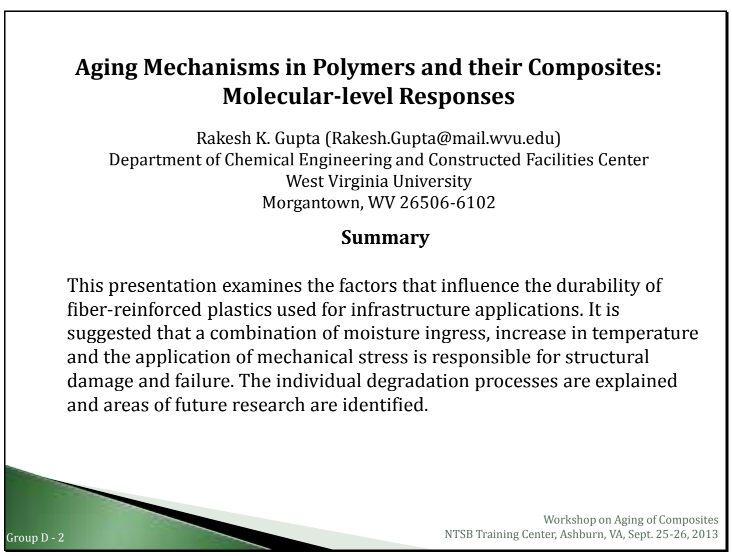
Group D - Slide 1



Group D - Slide 2



Group D - Slide 3

Causes of Degradation of FRP Composite Materials

- **Thermal Aging**
- **Atmospheric humidity**
- **Water immersion**
- **Wet/dry cycling**
- **Freeze-thaw cycling**
- **Contact with chemicals:** Salt, Deicing chemicals, Alkalis, Acids
- **Application of Mechanical Stress:** Creep and Fatigue
- **Ultraviolet and other radiation**
- **Fire**

More than one degradation agent may act at the same time

Temperature and Humidity changes and mechanical loading are probably the most important for durability of FRPs in Infrastructure Systems. Flammability requires separate treatment

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Group D - Slide 4

Detecting Degradation of FRP Composite Materials

- **Non-destructive**
  - **Ultrasonic testing**
  - **X-ray refraction topography**
  - **Infra-red thermography**
  - **Eddy current**
  - **Electrical resistance/conductivity**
- **Destructive**
  - **TEM**
  - **SEM** (including with vacuum)
  - **Differential scanning calorimetry**
  - **Dynamic mechanical analysis**

Group D - 4

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Group D - Slide 5

Reversible Changes – Simplest Situation

- **Uniform changes in temperature (no temperature gradients)**: Stress-strain behavior of composite is predictable. Need physical properties as a function of temperature. Matrix may become viscolealstic

- **Uniform changes in moisture concentration (no concentration gradients)**: Polymer glass transition temperature changes, often by tens of degree Celsius. The matrix polymer can swell; extent of swelling depends on thermodynamic properties. Stress-strain behavior of composite is predictable. Need physical properties as a function of concentration

- **Time scales of temperature and moisture concentration changes:** These can be predicted by solving the heat conduction equation and Fick's law of diffusion

Thin samples reach equilibrium faster than thick samples.
Transients can be ignored only for well-designed model experiments

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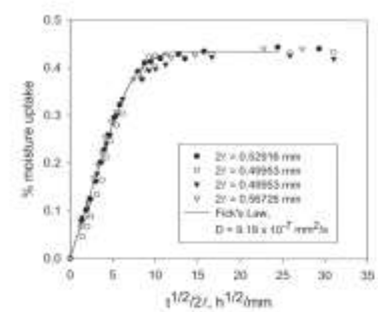
Group D - Slide 6

Diffusion Test Results



Water uptake curves for post cured neat vinyl ester resin samples at 25 °C in distilled water.

Group D - Slide 7

Irreversible Changes upon Increasing Temperature

- **Polymer Matrix:**
  - Physical aging can cause some shrinkage since material tends to equilibrium
  - Post curing occurs above Tg. Can cause an increase in molecular weight. Modulus will increase slightly, ductility will decrease slightly
  - Thermoplastics can crystallize
  - Thermal oxidation can lower molecular weight. Can lead to deterioration in mechanical properties
- **Fiber/Matix Interface**
  - Thermal expansion can cause composite weakening if there is a mismatch in the coefficients of thermal expansion between fiber and matrix

Above effects should be amenable to systematic study

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Irreversible Changes upon Increasing Moisture Concentration

- **Moisture Uptake:**
  - Depends on percentage of voids. Promoted by capillary action along fibers. Experimental measurements are needed
- **Polymer Matrix:**
  - Hydrolysis is possible, especially if polymer backbone contains polyesters, polyamides, polyimides or polycarbonates. Results in chain scission and a reduction in molecular weight . Rate of reaction can be measured in separate controlled experiments
- **In Presence of Stress:**
  - Amorphous polymers are susceptible to environmental stress cracking. Crazes can form rapidly and grow to become cracks that can lead to failure. Presence of corners can aggravate the situation. Needs study

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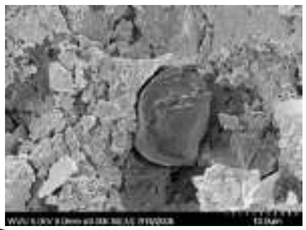
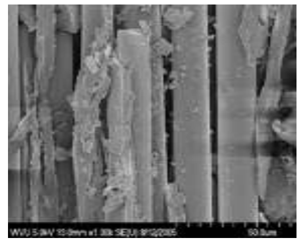
Irreversible Changes upon Increasing Moisture Concentration

- **Fiber Reinforcement:**
  - Aramid and glass fibers are prone to degradation. In glass fibers, moisture leaches out alkali oxides. Other reactions for aramids
  - Degradation of fibers can accelerate in the presence of stress. Needs quantification





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Methods of Improving Adhesive Bonding between Fiber and Matrix

- **Physical**
  - Cold plasma or electric discharge treatment. Results in etching, cleaning and surface roughening
- **Chemical**
  - Natural fibers are treated with alkali, acetic anhydride, benzoyl chloride, or maleic anhydride
  - Glass fibers are treated with silanes
  - Polymers can be grafted on to fiber surface. Act as coupling agents

Strength of interface depends on surface treatment. Rate of delamination should also depend on nature of surface treatment. No simple theory available for this

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Irreversible Changes upon Increasing Moisture Concentration

- **Osmosis:**
  - Products of hydrolysis or chemicals leached from glass fibers cannot diffuse out of gel coat. Instead water diffuses in so as to reduce the concentration of these chemicals
- **Consequences:**
  - Blistering of surface
  - Delamination at fiber/matrix interface
- **In Presence of Stress:**
  - Delamination is accelerated

Group D - Slide 12

Failure of Polymer Composites

- **Composite structure can be weakened in a variety of ways, by damage to matrix, fibers and/or the fiber/matrix interface**
- **Each damage process progresses at its own rate, but they may be synergistic effects**
- **What is observed is the result of all the processes acting together**
- **Challenge is to relate individual processes to overall observation in order to predict minimum service life**
- **Need is to find ways of mitigating composite aging – Better materials, improved processing, use of additives, protection from elements**

Group D - Slide 13

Suggestions for Future Research

- Select limited number of resin systems, fibers and composite geometries
- Make composite structures for durability testing by one or two processes
- Characterize composite structure
- Examine behavior of composite and its components over combined ranges of moisture content and temperature for extended periods of time. Determine cause of failure, and identify the weakest link
- Repeat above for creep and fatigue loading
- Develop durability correlations
- Look for ways to slow down the failure process

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Durability of FRP: The Key Role of Cold-Cured Thermosetting Resins

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International Workshop
Aging of Composites

Durability of FRP: The Key Role of Cold-Cured Thermosetting Resins

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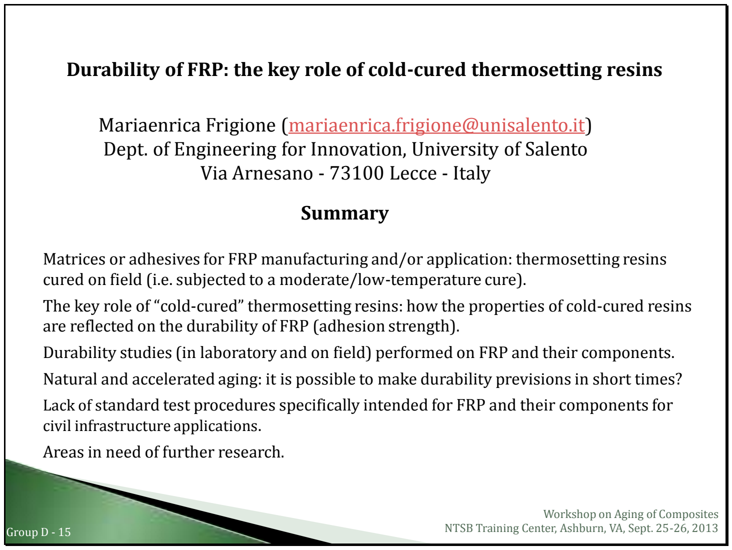
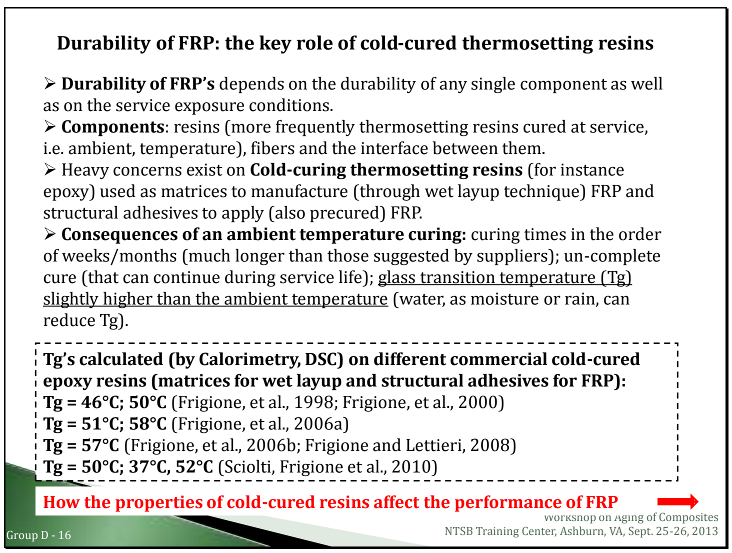
Group D - Slide 15



Group D - Slide 16



M. Frigione, M.A. Aiello, D. Acierno, Materials Engineering, Vol. 9, No. 3-4, pp. 225-235 (1998);
M. Frigione, C. Naddeo, D. Acierno, Materials Engineering, Vol. 11, No. 1, pp. 59-80 (2000)
M. Frigione, C. Naddeo, D. Acierno, Materials Engineering, Vol. 11, No. 1, pp. 59-80 (2000)
M. Frigione, M.A. Aiello, C. Naddeo, Construction and Building Materials, Vol. 20, pp. 957-970 (2006a) DOI: 10.1016/j.conbuildmat.2005.06.015
M. Frigione, M. Lettieri, A.M. Mecchi, Journal of Materials in Civil Engineering , Vol. 18, pp. 715-722 (2006b) DOI: 10.1061/(ASCE)0899-1561(2006)18:5(715)
M. Frigione, M. Lettieri, Journal of Polymer Science Part B: Polymer Physics, Vol. 46, pp. 1320-1336 (2008) DOI: 10.1002/polb.21466
M.S. Sciolti, M. Frigione, M.A. Aiello, Journal of Composites for Construction, Vol. 14, Issue 6, pp. 823-833 (2010). DOI: 10.1061/(ASCE)CC.1943-5614.0000132

Similar results can be also found in many other papers authored by:
Al-Mahaidi and co-workers, Keller and co-workers, Hollaway, Marouani and co-workers, Motavalli and co-workers, etc.

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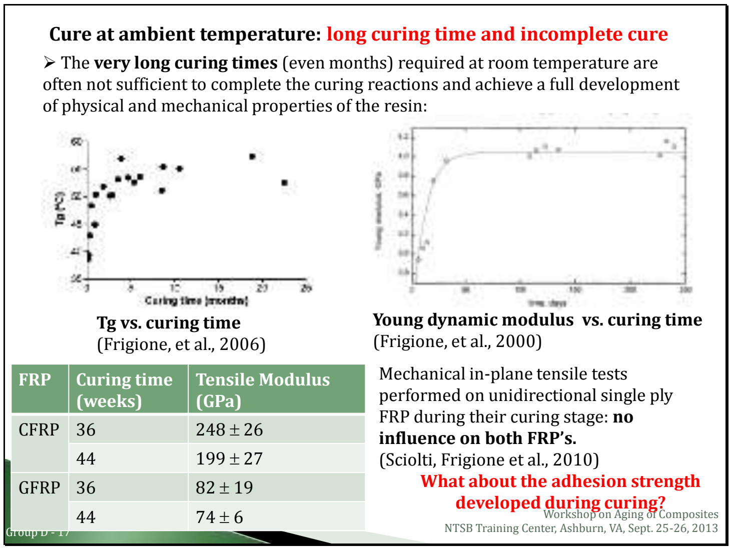

M. Frigione, M. Lettieri, A.M. Mecchi, Journal of Materials in Civil Engineering , Vol. 18, pp. 715-722 (2006) DOI: 10.1061/(ASCE)0899-1561(2006)18:5(715)
M. Frigione, A. Maffezzoli, D. Acierno, V.A.M. Luprano, G. Montagna, Polymer Engineering and Science, Vol. 40, No. 3, pp. 656-664 (2000).
M.S. Sciolti, M. Frigione, M.A. Aiello, Journal of Composites for Construction, Vol. 14, Issue 6, pp. 823-833 (2010). DOI: 10.1061/(ASCE)CC.1943-5614.0000132
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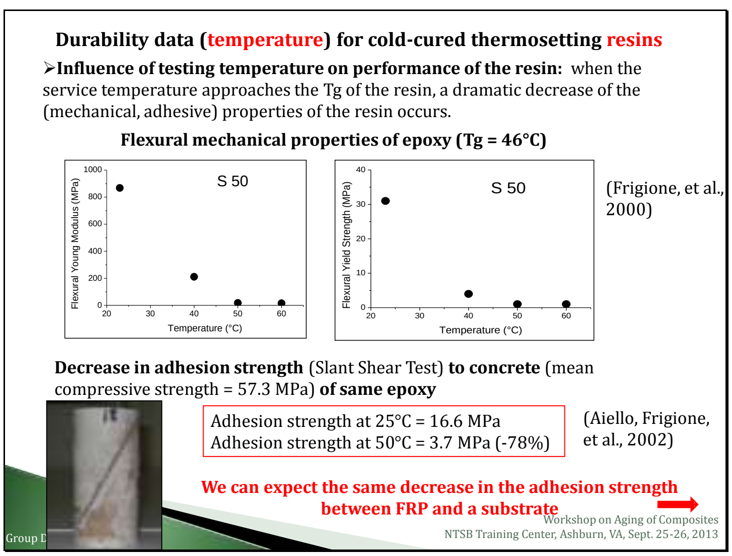

M. Frigione, C. Naddeo, D. Acierno, Materials Engineering, Vol. 11, No. 1, pp. 59-80 (2000).
M.A. Aiello, M. Frigione, D. Acierno, Journal of Materials in Civil Engineering, Vol. 14, No. 2, pp. 185-189 (2002). DOI: 10.1061/(ASCE)0899-1561(2002)14:2(185)
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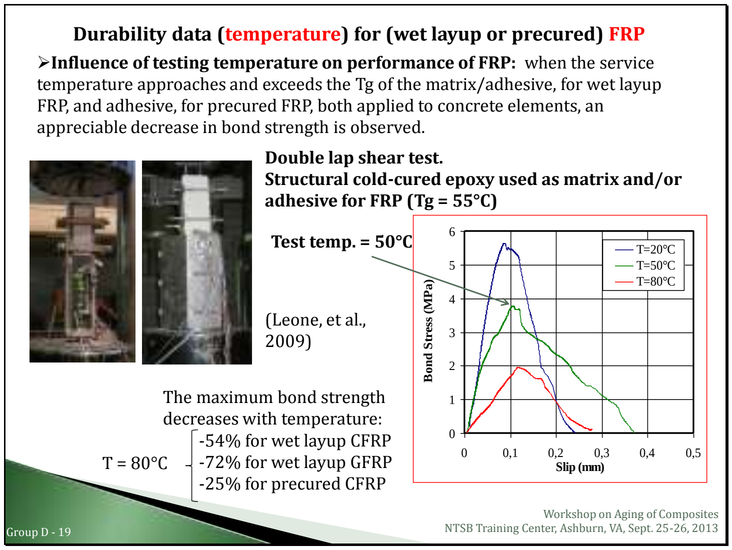

M. Leone, M. Stijn, M.A. Aiello, Composites: Part B, Vol. 40, pp. 85–93 (2009)
Similar results on FRP applied also to different substrates can be also found in other papers authored by: Al-Mahaidi and co-workers, Keller and co-workers, etc.

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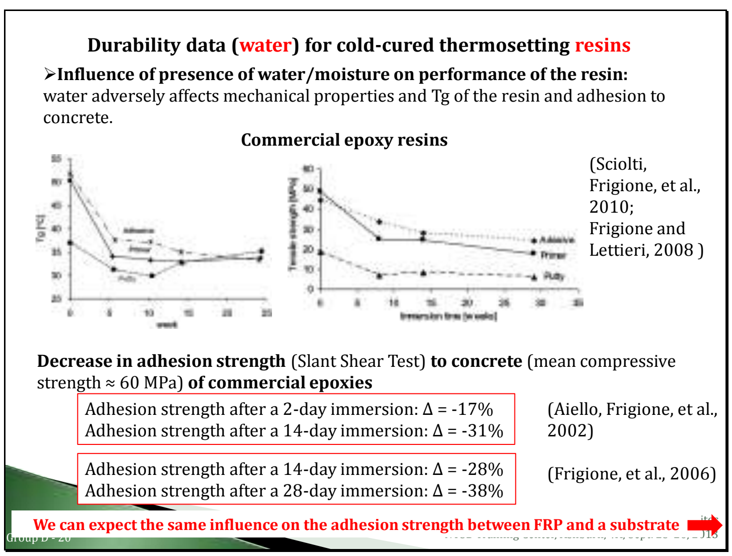

M.S. Sciolti, M. Frigione, M.A. Aiello: Journal of Composites for Construction, Vol. 14, pp. 823-833 (2010). DOI: 10.1061/(ASCE)CC.1943-5614.0000132
M. Frigione, M. Lettieri, Journal of Polymer Science: Part B: Polymer Physics, Vol. 46, 1320–1336 (2008). DOI: 10.1002/polb.21466
M.A. Aiello, M. Frigione, D. Acierno: Journal of Materials in Civil Engineering, Vol. 14, pp. 185-189 (2002). DOI: 10.1061/(ASCE)0899-1561(2002)14:2(185)
M. Frigione, M.A. Aiello, C. Naddeo, Construction and Building Materials, Vol. 20, pp. 957-970 (2006). DOI: 10.1016/j.conbuildmat.2005.06.015

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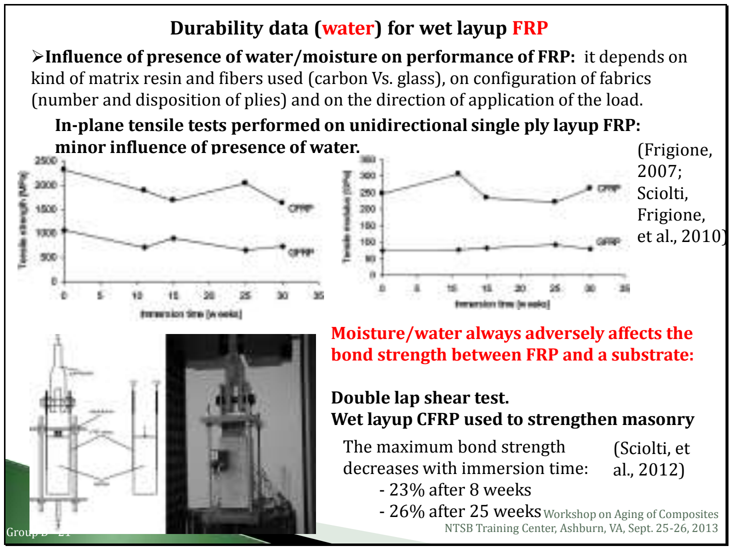

M.S. Sciolti, M. Frigione, M.A. Aiello, Journal of Composites for Construction, Vol. 14, pp. 823-833 (2010). DOI: 10.1061/(ASCE)CC.1943-5614.0000132

M.S. Sciolti, M.A. Aiello, M. Frigione, Composites Part B: Engineering, Vol. 43, pp. 3239-3250 (2012). DOI: 10.1016/j.compositesb.2012.03.002

Review paper:

M. Frigione: “Durability Aspects of Polymer Composites Used for Restoration and Rehabilitation of Structures”. In: “Leading-Edge Composite Material Research”, Tobias G. Wouters Ed., Ch 1, pp. 23-69 (2007). ISBN: 978-1-60021-995-5. Nova Science Publishers, Inc. New York, USA, 2007.

Similar results on FRP applied to concrete/masonry can be also found in other papers authored by:
Lourenço and co-workers, Silva and co-workers, Dai J.-G. and Yokota H. and co-workers.

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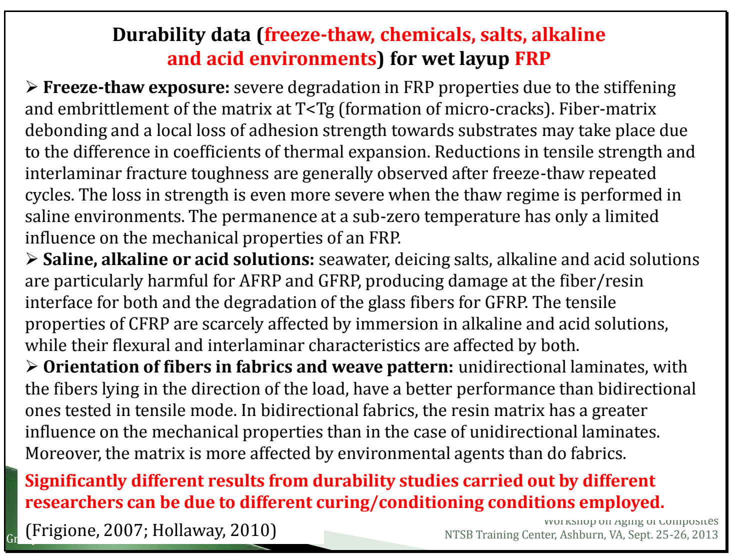

Review papers:

M. Frigione: “Durability Aspects of Polymer Composites Used for Restoration and Rehabilitation of Structures”. In: “Leading-Edge Composite Material Research”, Tobias G. Wouters Ed., Ch 1, pp. 23-69 (2007). ISBN: 978-1-60021-995-5. Nova Science Publishers, Inc. New York, USA, 2007.

L.C. Hollaway, Construction and Building Materials, Vol. 24, pp. 2419-2445 (2010).

Similar results can be also found in many other papers, among them those authored by Al-Mahaidi and co-workers.

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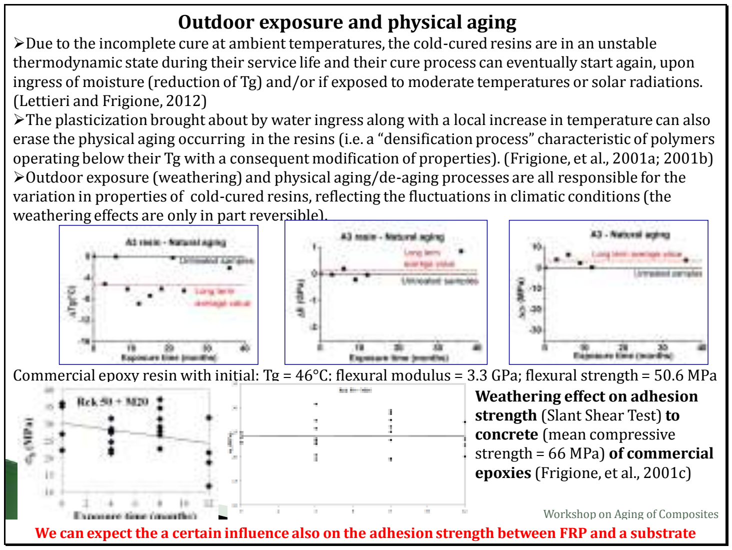

M. Frigione, C. Naddeo, D. Acierno, Journal of Polymer Engineering, Vol. 21, No. 1, pp. 23-51 (2001a).
M. Frigione, C. Naddeo, D. Acierno, Journal of Polymer Engineering, Vol. 21, No. 4, pp. 349-367 (2001b).
M. Frigione, M.A. Aiello, D. Acierno, Materials Engineering, Vol. 12, No. 3, pp. 443-454 (2001c).
M. Lettieri, M. Frigione, Journal of Applied Polymer Science, Vol. 119, Issue 3, pp. 1635-1645 (2011). DOI: 10.1002/app.32835.
M. Lettieri, M. Frigione, Construction and Building Materials, Vol. 30, pp. 753–760 (2012).
Review paper:
M. Frigione: "Durability of Adhesives and Matrices for Polymer Composites used in Restoration and Rehabilitation of Building Structures under Natural and Accelerated Weathering Conditions". In: "Encyclopedia of Polymer Composites: Properties, Performance and Applications", Mikhail Lechkov and Sergej Prandzheva Eds., Ch 8, pp. 319-344 (2010). ISBN: 978-1-60741-717-0. Nova Science Publishers, Inc. New York, USA, 2010.

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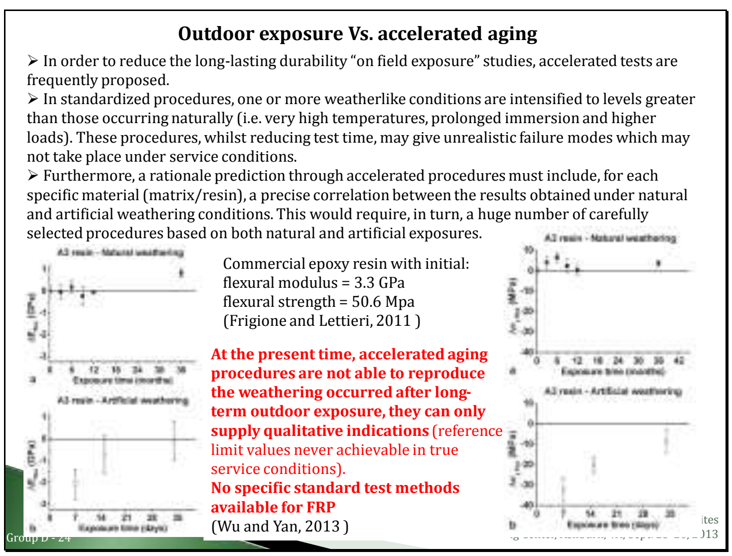

M. Lettieri, M. Frigione, Journal of Applied Polymer Science, Vol. 119, Issue 3, pp. 1635-1645 (2011). DOI: 10.1002/app.32835.
H.-C. Wu, A. Yan, Composites: Part B, Vol. 51, pp. 162-168 (2013).

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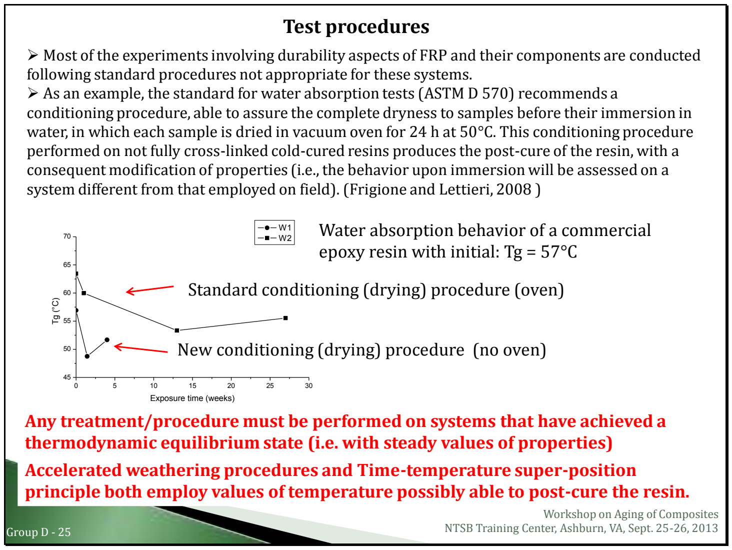

M. Frigione, M. Lettieri, Journal of Polymer Science: Part B: Polymer Physics, Vol. 46, 1320–1336 (2008). DOI: 10.1002/polb.21466

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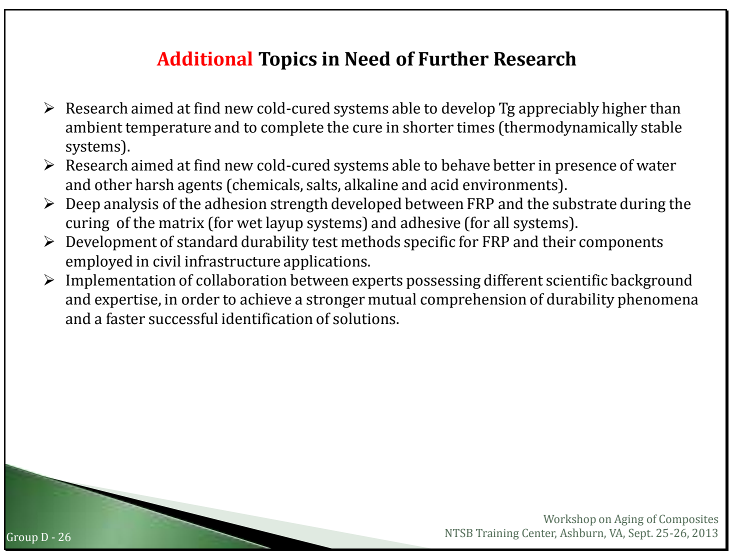

Recommendations for research procedures:

•Attention must be always paid to the curing conditions used (curing temperature & time) since these latter severely affect the response of the materials/system to any durability test.

•A comparison of results from durability tests is practicable (and useful) only if comparable curing/conditioning conditions are employed.

•The Tg of the resin should be preferably determined using DSC instead of DMTA (only). With DSC is possible to assess the degree of cure of the resin, which is not possible by using DMTA. The results from DSC are, in addition, more accurate than those obtained by DMTA (especially when the Tg is calculated by the peak of tan delta).

Variable Amplitude Fatigue Lifetime Predictions for FRP Composites

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Virginia Tech, Department of Engineering Science and Mechanics
495 Old Turner Street, Blacksburg, VA 24061

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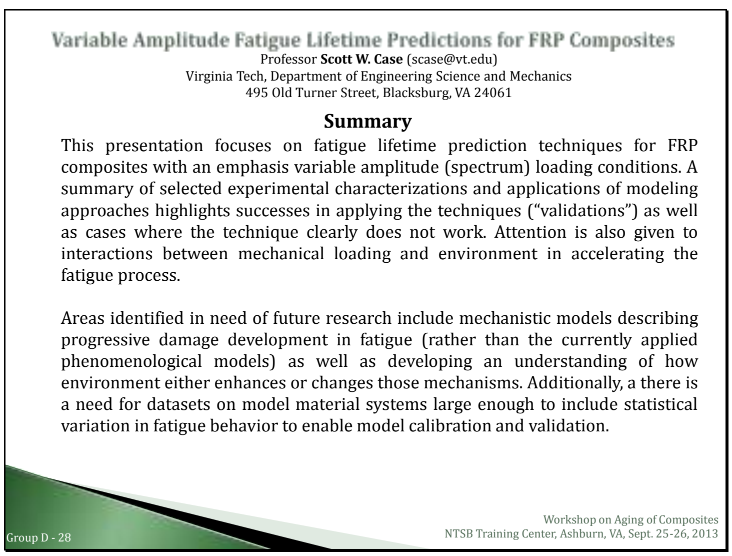

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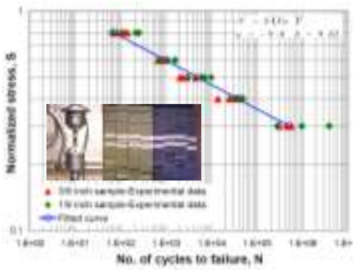
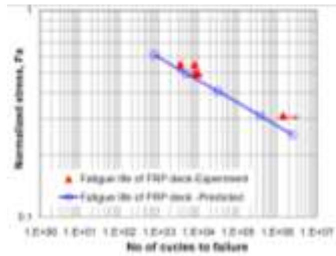
Example of Previous Fatigue Work on Bridge Deck





Use coupon-level data + analysis (finite element stress analysis, residual strength-based lifetime prediction) to predict observed structural-level failures for constant amplitude fatigue loading.

http://scholar.lib.vt.edu/theses/available/etd-04252008-115141/unrestricted/Dissertation_Prasun_Majumdar.pdf

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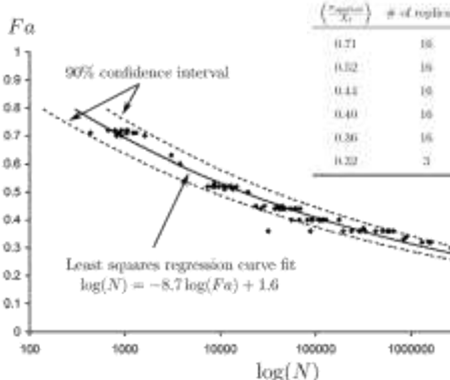
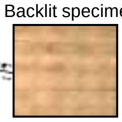
Why is variable amplitude fatigue an issue?

88 Sample S-N data



Fa	# of replicates	Lifetime, N (cycles) median	Weibull α	Weibull β
0.71	16	917	3.8	1004
0.52	16	11162	4.3	12517
0.44	16	44010	3.7	50422
0.40	16	109397	4.2	116877
0.36	16	377012	1.4	471390
0.32	3	1542753	-	-

Backlit specimen during fatigue


Initial cycle


3450 cycles

http://dx.doi.org/10.1016/j.engfracmech.2007.03.002

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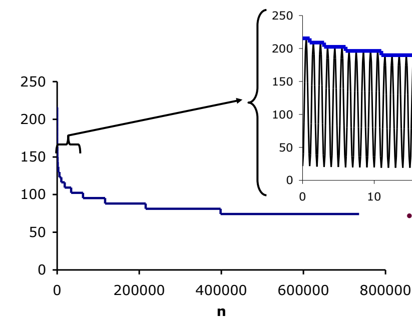
Now for the interesting part: Spectrum Loading

- 22 Stress level spectrum (74 - 215 MPa)
- 735641 total cycles, R = 0.1, sinusoidal loading



- Applied as:
  - Descending Ordered Blocks
  - Ascending Ordered Blocks
  - "Completely Randomized"

http://dx.doi.org/10.1016/j.engfracmech.2007.03.002

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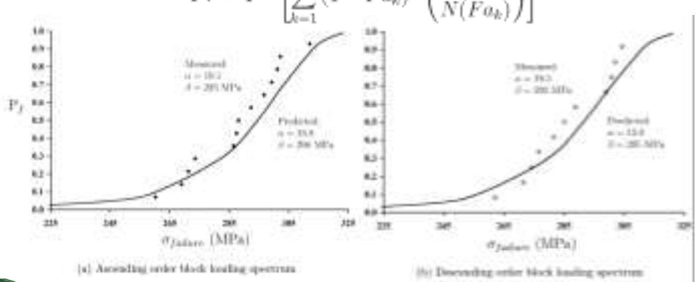
Spectrum Residual Strength Distributions

- Prediction uses UTS strength distribution as input.
- Strength-life equal rank assumption (impossible to verify experimentally)

$$Fr = 1 - \left[\sum_{k=1}^{n} (1 - Fa_k)^{\frac{1}{3}} \left(\frac{1}{N(Fa_k)} \right) \right]^{j}$$



http://dx.doi.org/10.1016/j.engfracmech.2007.03.002

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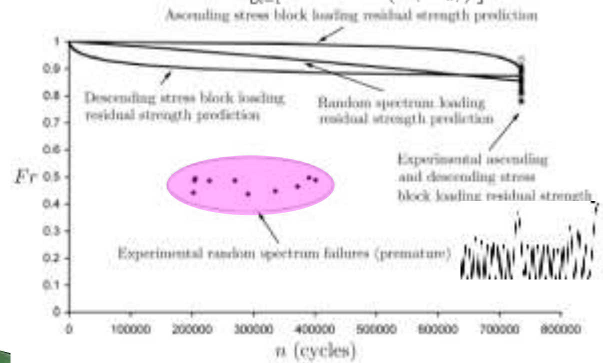
Spectrum Residual Strength Evolution

$$Fr = 1 - \left[\sum_{k=1}^{n} (1 - Fa_k)^{\frac{1}{j}} \left(\frac{1}{N(Fa_k)}\right)\right]^j$$



http://dx.doi.org/10.1016/j.engfracmech.2007.03.002

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Examples of Existing Datasets and Models for Variable Amplitude Fatigue

Material ID	Fiber	Matrix	Laminate structure	Fiber Volume Fraction	Data source	Spectrum loading
DD16	E-glass	Ortho-polyester	$[90/0/\pm45/0]_s$	0.36	DOE/MSU	WISPERX, WISPK, WISXR01
MD2	E-glass	Prime 20 epoxy	$[[\pm45/0]_4/\pm45]$	0.52	OPTIDAT	WISPER, WISPERX
UD2	E-glass	Prime 20 epoxy	$[0]_4$	0.52	OPTIDAT	WISPER
VT8084	Woven E-glass	Ashland VE 8084	$[0/+45/90/-45/0]_s$	0.52	Virginia Tech	RAY95, RAY95R01

Material	**VT8084**	**VT8084**	**VT8084**
Spectrum	**RAY95**	**RAY95**	**RAY95R01**
Average exp. N	**265000**	**916000**	**150000**
# Spectrum repeats	**53.1**	**183**	**30.1**
Model	$M_e = \log(\frac{N_{model}}{N_{experiment}})$		
Palmgren-Miner	0	0.06	0.27
Bond and Farrow	1.85	1.92	0.26
Hashin and Rotem	-0.01	0.05	0.27
Broutman and Sahu	-0.07	0.01	0.17
Reifsnider and Stinchcomb	-0.03	0.04	-0.01
Yang and Liu	-0.12	-0.05	-0.32
Adam et al.	-0.06	0.02	0.17

Note: All but one depends explicitly on S-N curve

http://dx.doi.org/10.1016/j.ijfatigue.2008.07.002

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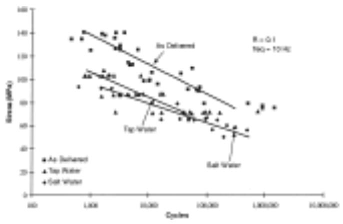
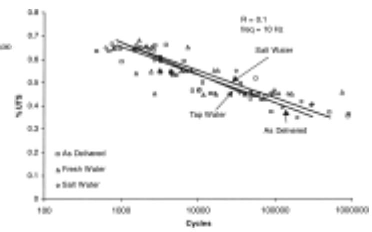
Effect of Environment: Moisture





As expected, samples that were water-aged exhibited poorer performance than those that were not water aged.

Fatigue lifetimes scale with residual ultimate strength. (Slope is approximately -10%/decade.)

http://dx.doi.org/10.1016/S0142-1123(99)00100-0

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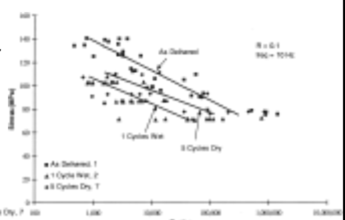
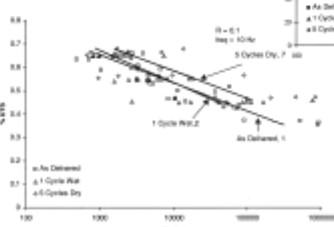
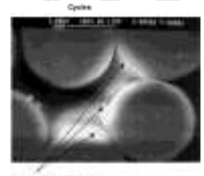
Effect of Environment: Moisture

Prior moisture cycling influences fatigue response



Scaling with ultimate strength is somewhat less convincing (considerable scatter)





http://dx.doi.org/10.1016/S0142-1123(99)00100-0

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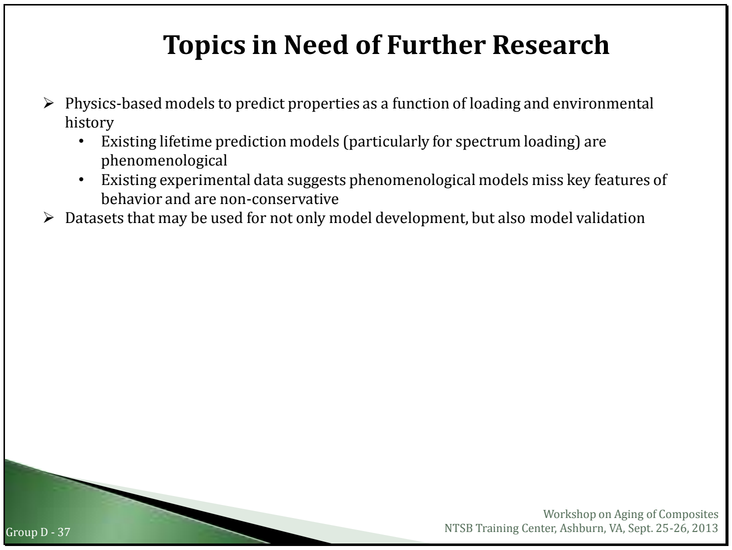

Aging and Durability Issues for Fiber Reinforced Polymers

Samit Roy (sroy@eng.ua.edu)
Professor, Department of Aerospace Engineering and Mechanics
University of Alabama, Tuscaloosa

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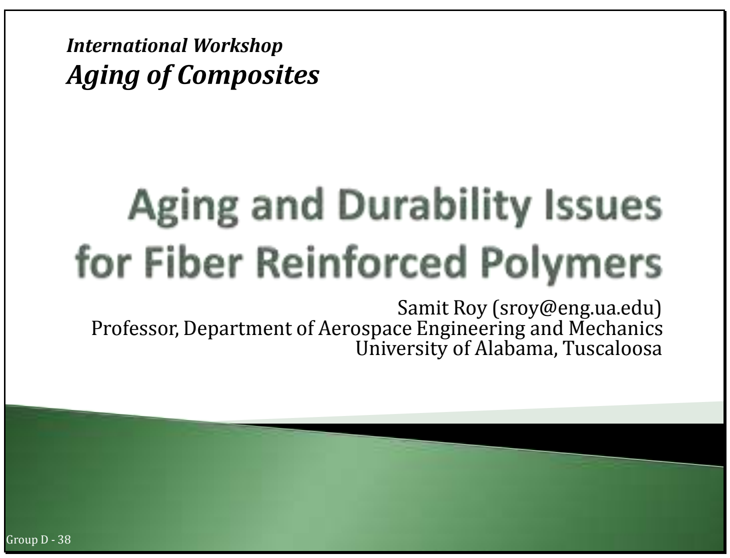

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AGING AND DURABILITY MODELING ISSUES FOR FIBER REINFORCED POLYMERS

Samit Roy
Professor, Department of Aerospace Engineering and Mechanics
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Presented at the FHWA Workshop on Aging of Composites
September 25-26, 2013
Ashburn, VA

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Areas in Need of Further Research

- Standard durability models available today for life prediction of FRP are primarily empirical or phenomenological models, developed mainly by curve fitting test data
- Test matrix has to be repeated if a new FRP system is introduced or if the environment changes beyond what is in the test matrix
- Synergistic interactions between various environmental factors (stress, humidity, pH, temperature) are frequently not included
- A mechanism-based model removes some, if not all, of the empiricism
- There is need to develop a synergistic mechanism-based life prediction model for FRPs in aggressive environment by synergistically incorporating load history and loading rate effects
- Use of Molecular Dynamics (MD) with appropriate force fields to study synergistic interactions at the polymer molecular level and at fiber matrix interface
- Multi-scale modeling (nano-micro-macro) is required to perform life-prediction at the macro-scale

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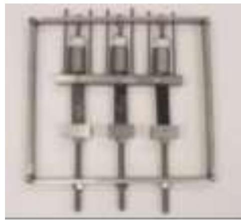
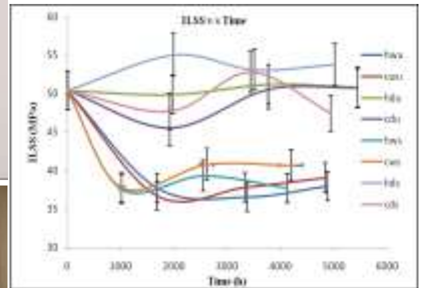
Aging Data Available: Short Beam Shear Test (STTR, 2009)





Ref: "Characterization and Modeling of the Effect of Environmental Degradation on Interlaminar Shear Strength of Carbon/Epoxy Composites," *P. and Poly Comp.*, Vol. 16, No. 3, Pp. 165-170.

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Methods of Assessing Durability Issues of FRPs: Interface Cohesive Layer Model Incorporating Rate and Load History Effect to Model Debond and Delamination in Aggressive Environments

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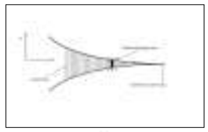
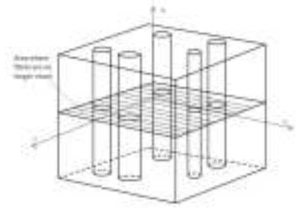
Micromechanics Based Cohesive Layer with Coupled Viscoelasticity and Damage





$$\alpha(t) = \frac{A - \sum_{k=1}^{N} A_k(t)}{A}$$

$$\bar{\sigma}_{ij}(t) = (1-\alpha(t))\ \sigma_{ij}^{\text{fibril}}(t)$$

$$\{\sigma(t)\}^{\text{fibril}} = [C(t)](\{\varepsilon(t)\} - \{H(t)\})$$

$$\{\bar{\sigma}(t)\} = (1-\alpha(t))[C(t)](\{\varepsilon(t)\} - \{H(t)\})$$

Cohesive RVE showing polymer fibrils*

Ref: Allen, D.H. and Searcy, C.R, *International Journal of Fracture*, Vol. 107, No. 2, 159-176, (2001).
Roy, S. and Reddy, J.N., *International Journal for Numerical Methods in Engineering*, 2531-2546, (1988).

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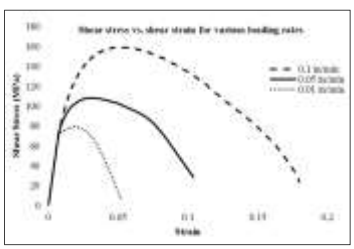
Cohesive Damage Evolution Law



Rate dependent cohesive traction-separation law*

$$\frac{d\alpha}{dt} = \begin{cases} \alpha_0 \bar{\lambda}^m, & \text{if } \dot{\lambda} \geq 0 \text{ and } \alpha < 1 \\ 0, & \text{if } \dot{\lambda} < 0 \text{ and } \alpha < 1 \end{cases}$$

$$\bar{\lambda}(t) = \lambda_I(t) - \lambda_{CR}\ , \quad \lambda_I(t) \geq \lambda_{CR}$$

where, λ_{CR} is the value of critical stretch at failure initiation

Viscoelastic cohesive layer is an effective way of simulating rate-dependent delamination/debond in composites with hygrothermal degradation included in λ_{CR}, m, α_0 , without recourse to a specified traction-separation law

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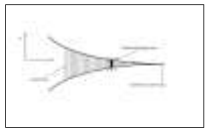
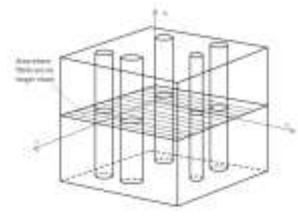
Micromechanics Based Cohesive Layer for Hygrothermal Degradation in FRP



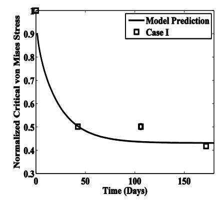
$$\frac{\partial m_1}{\partial t}+\frac{\partial m_2}{\partial t}=D_m\frac{\partial^2 m_1}{\partial x^2}$$

$$N(t)=N_0[Z\exp\left(-\frac{M_2(t)}{dN_0}\right)-(Z-1)]$$



Cohesive RVE showing polymer fibrils*

$$\sigma_{VMC}(t)=\boldsymbol{N}(t)\sigma_{VM0}/\boldsymbol{No}$$



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Aging Data Available: Characterization of Damage Constants for Delamination after Thermal Aging of FRP

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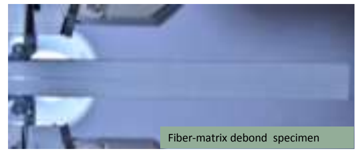
Double Cantilever Beam (DCB) Specimen for Characterizing Damage Parameters in IM7/BMI due to Thermal Aging at 260 C for 1000 hours



Dimensions of DCB Specimens (mm)		
	Delamination	Debond
Length	140	140
Width	14	2.38
Thickness	2.38	14
Initial crack length	70-80	70-80

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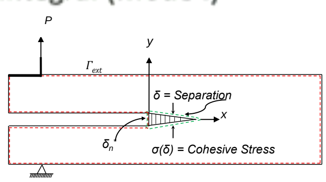
Evaluation of Cohesive Stresses from J-integral (Mode I)



$$J = \int_{\Gamma} W dy - T_i \frac{du_i}{dx} ds$$

$$J_{\text{int}} = -\int_{\Gamma_{\text{int}}} T_y \frac{\partial v}{\partial x} ds = -\int_{\Gamma_{\text{int}}} \sigma_n(\delta_n, \dot{\delta}_n) \frac{d\delta_n}{dx} dx = \int_0^{\delta_n^*} \sigma_n(\delta_n, \dot{\delta}_n) d\delta_n$$

$$J_{ext} = \frac{2P\theta}{b} \qquad J_{\text{int}} = J_{ext}$$

$$\sigma_n(\delta_n, \dot{\delta}_n) = \frac{\partial J_{ext}}{\partial \delta_n}$$

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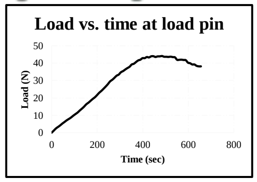
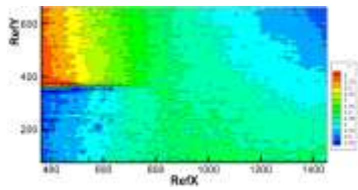
Evaluation of Cohesive Stresses from J-integral using Digital Image Correlation





Y displacement field from DIC analysis

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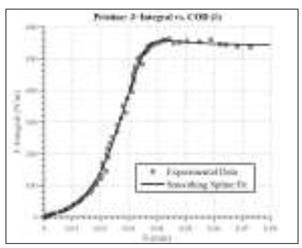
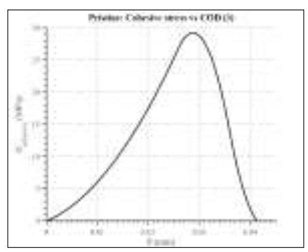
Calculation of Cohesive Stress using J-integral for IM7/BMI for Delaminatiion (Unaged Baseline Case, room temperature)*





$J = \frac{2P\theta}{b}$

$\sigma_I = \frac{\partial J}{\partial \delta}$

P: Reaction force at the pin location.
θ: Rotation at the pin location.
δ: Separation at the crack tip in y direction.

*Ref: P. Upadhyaya, S. Roy, M. Haque, H. Lu , "A novel numerical–experimental approach for predicting delamination in high temperature polymer matrix composites", *Composite Structures*, 104 (2013) 118-124.

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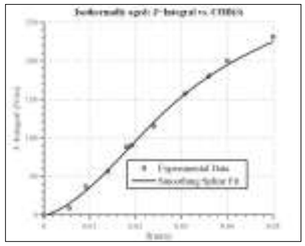
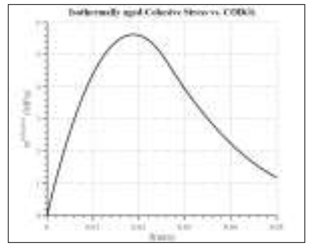
Calculation of Cohesive Stress using J-integral for IM7/BMI for Delaminatiion (Isothermally Aged in Air for 1000 hrs. at 260 C)





$J = \frac{2P\theta}{b}$ $\sigma_I = \frac{\partial J}{\partial \delta}$

P: Reaction force at the pin location.
θ: Rotation at the pin location.
δ: Separation at the crack tip in y direction.

Test data indicate 79 % reduction in peak cohesive stress , from 27 MPa to 5.6 MPa due to thermal aging

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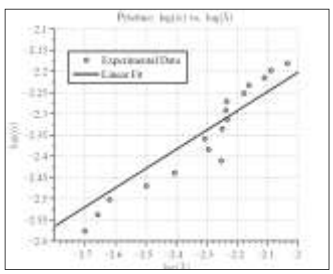
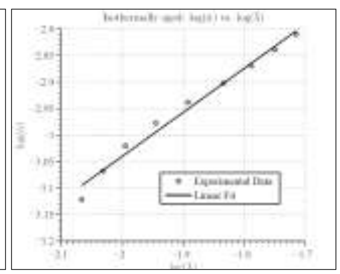
Evaluation of Damage Parameters





$$\frac{d\alpha}{dt} = \begin{cases} \alpha_0 \bar{\lambda}^m, & if\ \dot{\lambda} \geq 0 \\ 0, & if\ \dot{\lambda} < 0 \end{cases}$$

$$Log(\dot{\alpha}(t)) = Log\alpha_0 + mLog\bar{\lambda}$$

	λ_{cr}	α_0	m
Pristine	1.0264	0.507	0.46
Aged	1.0149	0.115	0.83

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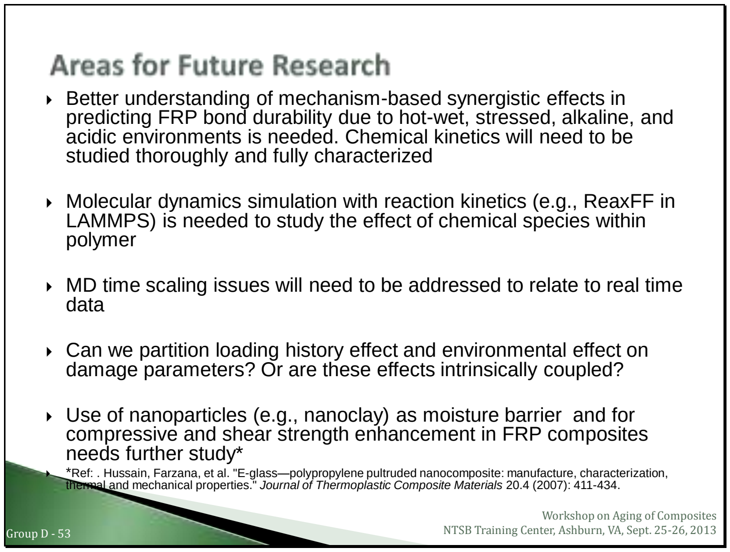

A Model to Predict the Degradation of FRP Bonded Concrete Joints in Moist Environment

Baolin Wan (baolin.wan@marquette.edu)
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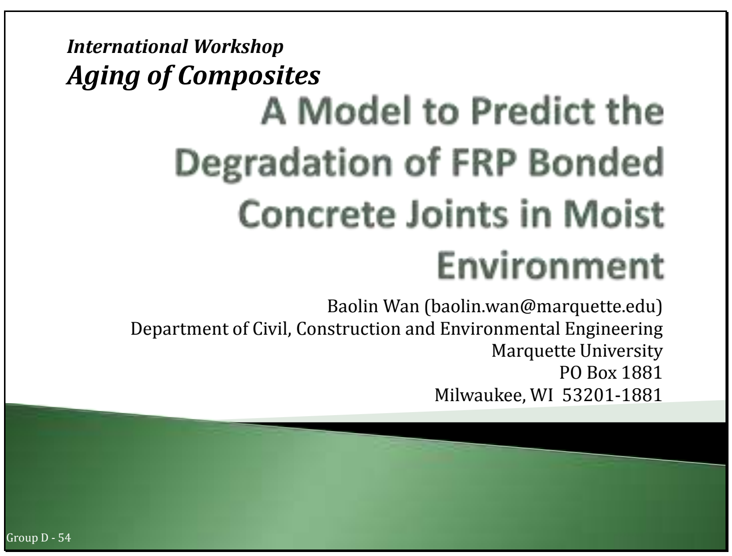

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A Model to Predict the Degradation of FRP Bonded Concrete Joints in Moist Environment

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This study proposed a bond mechanism based deterioration model of bond interfacial fracture energy for FRP-concrete joints in moist environments. The bond interface region relative humidity (IRRH) in moist environment was correlated to the bond fracture energy in this deterioration model. The IRRH-dependent interface separation-tractions were derived in the frame of cohesive zone model (CZM). Such an IRRH-dependent interface separation-traction law was simulated by a series of non-linear interface elements attached to the bond interface to calculate the macroscopic load-displacement curves for the Modified Double Cantilever Beam (MDCB) specimens. Through moisture diffusion analysis, IRRH were determined as a function of the moisture exposure time for given specimen dimension and environmental RH. Using IRRH as the bridge, the time-dependent load-displacement curves of the MDCB specimens were obtained. The good agreement with the experimental data indicated that the model worked well. The approach developed in this study can be used to simulate and predict the durability of bond between FRP and concrete in moist environments.

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Moisture Deteriorating FRP/Concrete Bond

- The common environmental factors include (but are not limited to): moist environments, acidic environments (salt solution), alkaline environments (alkaline solution in concrete and soil), freeze-thaw cycling, wet-dry cycling, high temperature, temperature variation, ultraviolet (UV) radiation, etc.
- Most environmental factors are directly related to or partially coupled with moisture. Understanding the moisture effect on the durability of the FRP-concrete bond is very helpful for the solution of other durability problems.
- Moisture can decrease the free surface energy of bond interface, lower the adhesion strength, degrade the strength and stiffness of adhesive, and cause vapor and osmotic pressure.
- Exposure to moisture will cause the failure mode changing from cohesive failure in concrete to adhesive failure in interface.

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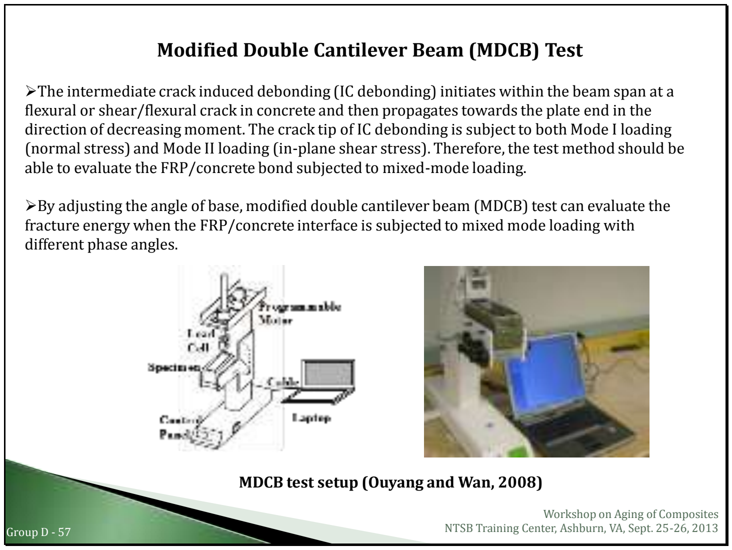

Ouyang, Z. and Wan, B. (2008), "Experimental and Numerical Study of Moisture Effects on the Bond Fracture Energy of FRP/Concrete Joints", Journal of Reinforced Plastics and Composites, Vol. 27, No. 2, pp. 205-223.

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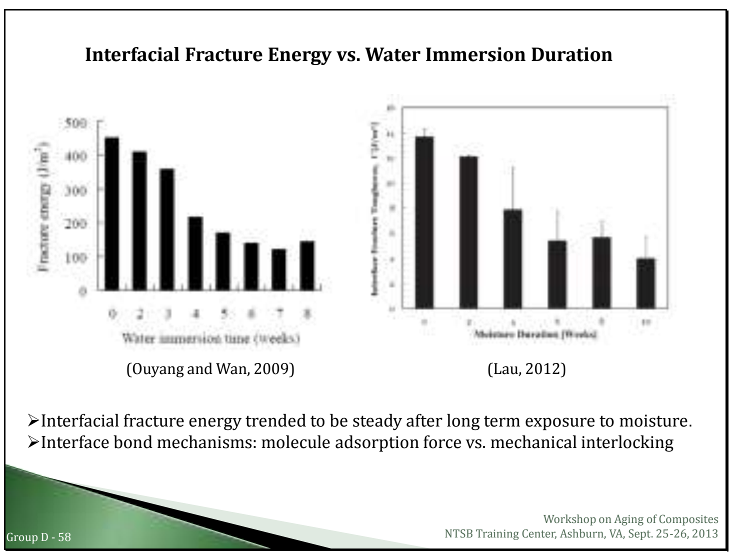

Ouyang, Z. and Wan, B. (2009), "Nonlinear Deterioration Model for Bond Interfacial Fracture Energy of FRP-Concrete Joints in Moist Environments", ASCE Journal of Composites for Construction, Vol. 13, No. 1, pp. 53-63.
Lau, D. (2012), "Moisture-induced Debonding in Concrete-epoxy Interface", The Hong Kong Intuition of Engineering Transactions, Vol. 19, No. 3, pp 33-38.

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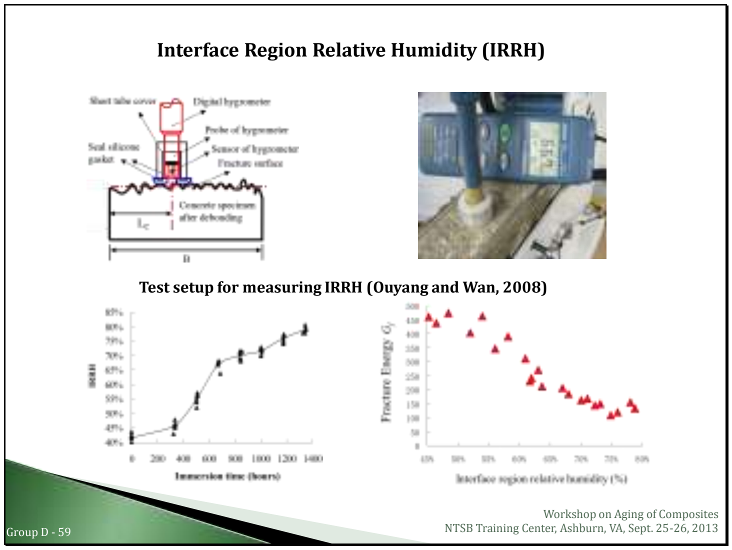

Ouyang, Z. and Wan, B. (2008), "Modeling of Moisture Diffusion in FRP Strengthened Concrete Specimens", ASCE Journal of Composites for Construction, Vol. 12, No. 4, pp. 425-434.

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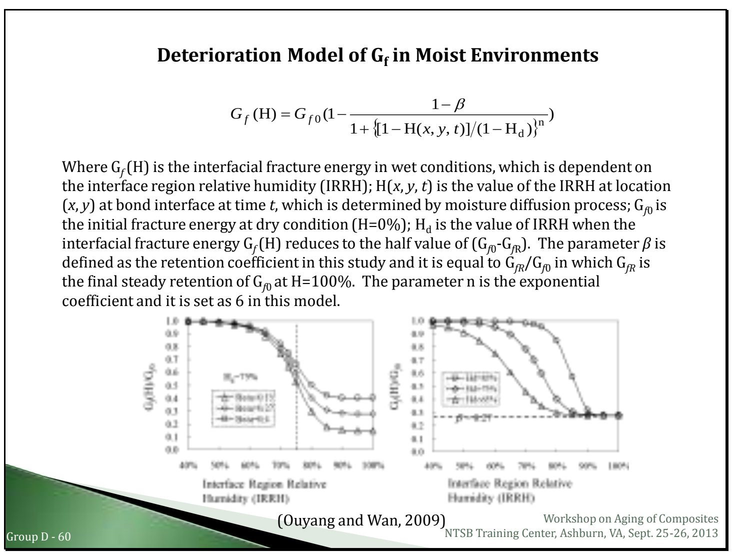

Ouyang, Z. and Wan, B. (2009), "Nonlinear Deterioration Model for Bond Interfacial Fracture Energy of FRP-Concrete Joints in Moist Environments", ASCE Journal of Composites for Construction, Vol. 13, No. 1, pp. 53-63.

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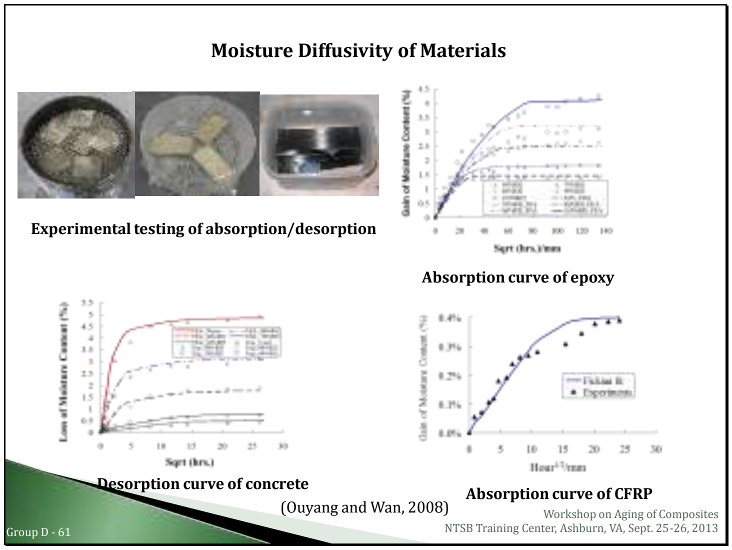

Ouyang, Z. and Wan, B. (2008), “Modeling of Moisture Diffusion in FRP Strengthened Concrete Specimens”, ASCE Journal of Composites for Construction, Vol. 12, No. 4, pp. 425-434.

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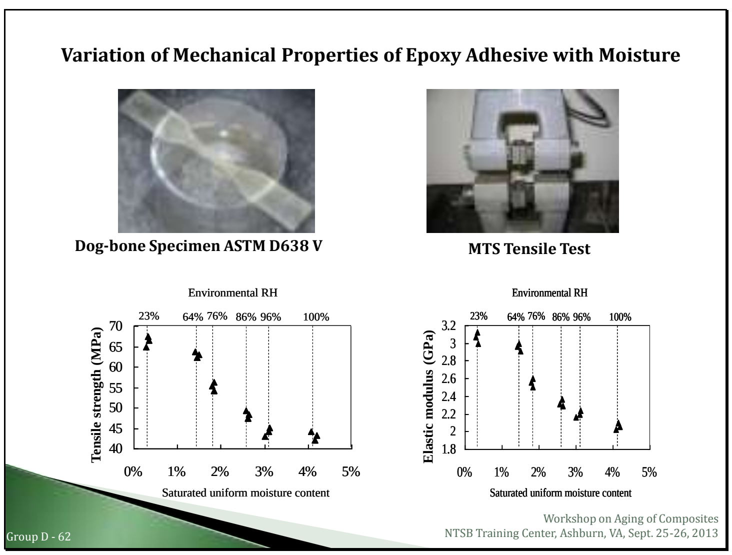

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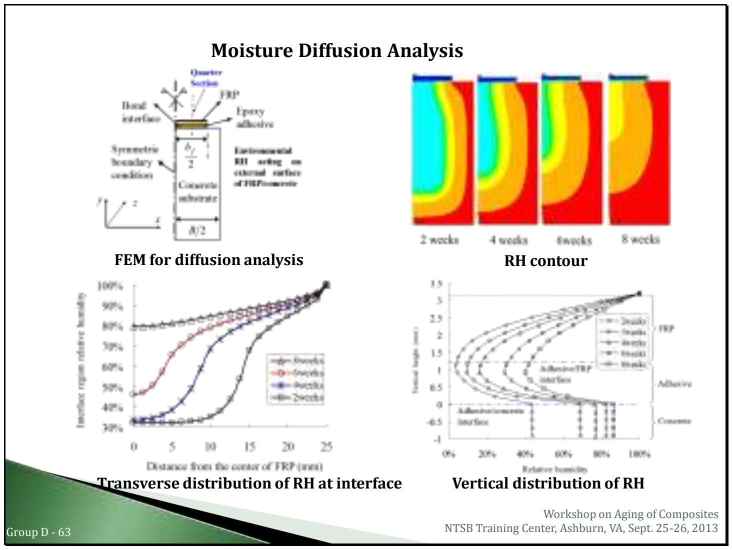

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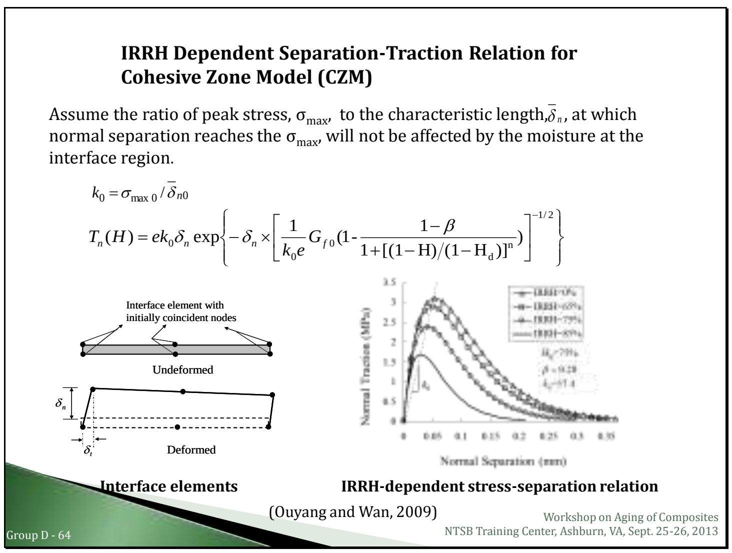

Ouyang, Z. and Wan, B. (2009), “Nonlinear Deterioration Model for Bond Interfacial Fracture Energy of FRP-Concrete Joints in Moist Environments”, ASCE Journal of Composites for Construction, Vol. 13, No. 1, pp. 53-63.

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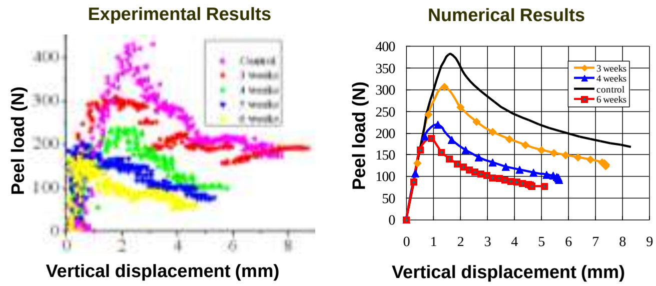
Load-Deflection Curves of MDCB Specimens at Different Immersion Duration



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Areas in Need of Further Research

- An advanced micro-level experimental test is needed to measure the contribution of mechanical interlocking and adsorption for the FRP/concrete bond.
- The loading phase angle effects on the bond deterioration are needed to investigate.
- Diffusion analysis is needed for FRP/concrete system with variable environmental temperature, variable environmental relative humidity, and wet-dry cycle.
- Large scale testing and modeling are needed to validate/modify this small scale model to be able to predict the life of FRP repaired/retrofitted concrete structure in moist environment.
- Long term field monitoring is needed to validate the life prediction model.

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Appendix A: Workshop Participants

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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		X		
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		X		
Ray Liang	WVU-CFC			X	
Weiqing Liu	Nanjing U of Tech, China		X		
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	