Center for Integration of Composites into Infrastructure

West Virginia University

Site Director: Udaya B. Halabe, Ph.D., P.E., ASCE Fellow

Date: February 1, 2011

West Virginia University

Status of the Site

- WVU recently purchased a 220-kip Instron universal testing machine to replace a similar machine acquired in 1936.

- NSF support for government agencies to join should allow WVDOT-DOH and WV-DOE to join, as they have been very interested.

List of Projects at WVU

- WVU-1: Resin Design for Fire Safety Requirements
- WVU-2: Strength and Fatigue Life Prediction
- WVU-3: Aging Testing and Analysis of Composites
- WVU-4: Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)
- WVU-5: Design, Manufacture and Implementation of Structural Panels

Resin Design for Fire Safety Requirements

Project Number: WVU-1

- Project Manager / PI: Rakesh Gupta
- Overview
  - FRPs are susceptible to heat and fire: upon heating, matrix decomposes, releasing volatiles that act as fuels, there is fire spread and emission of toxic smoke and soot
  - There is loss of mechanical properties and structural integrity
  - Flame retardants in polymer can delay combustion
  - Knowledge of sequence of events that lead to fire can be used to understand and improve material behavior
- Budget Update

Resin Design for Fire Safety Requirements

Project Number: WVU-1

- Progress to Date
  - Computational methods can be used to determine influence of heating on a composite structure
  - Good agreement shown between calculations and data for ignition temperature of polymers subjected to UL-94 test
  - COMSOL Software now is used to simulate the decomposition of FRPs upon heating at prescribed rate
  - Time- and position-dependent temperature and gas emission profiles have been calculated
  - Computations agree with experiments reported in the literature

Resin Design for Fire Safety Requirements

Project Number: WVU-1

Physical Situation

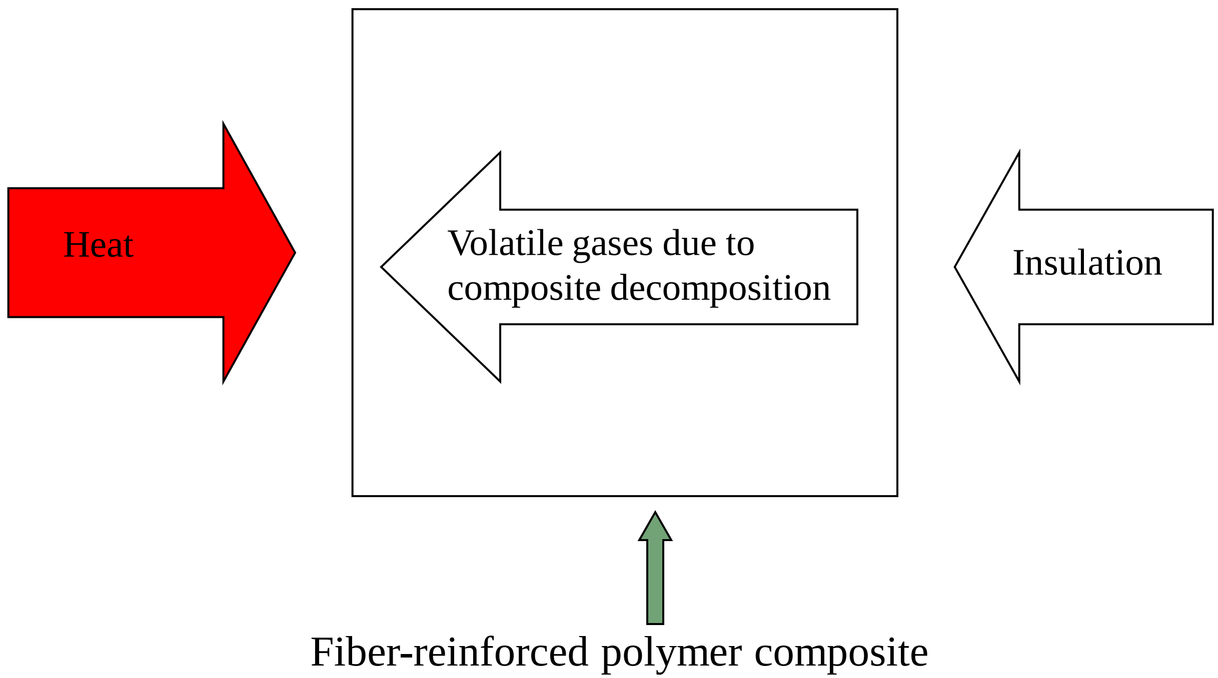


Figure 1. Schematic diagram of decomposition of a composite

Resin Design for Fire Safety Requirements

Project Number: WVU-1

Governing equations

Energy balance

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \dot{m}_g C_{pg}\frac{\partial T}{\partial x} + \left(-\frac{\partial \rho}{\partial t}\right)\left(h - h_g + Q\right)$$

Accumulation — Conduction — Convection — Convection — Accumulation — Heat generation or consumption

T, temperature [K]; t, time [s]; ρ, density [kg/m^3]; k, thermal conductivity [W/(m*K)];

C_p and C_{pg}, heat capacity of composite and gases [J/(kg*K)];

$\dot{m}_g$, gases mass flux [kg/(s.m^2)]; Q, heat consumption or generation [J/kg];

H and H_g, enthalpy of composite and gases [J/kg]

Resin Design for Fire Safety Requirements

Project Number: WVU-1

Governing equations

Mass balance

$$\frac{\partial \rho}{\partial t} = -\frac{\partial \dot{m}_g}{\partial x}$$

Decomposition reaction

Arrhenius equation

$$\frac{\partial \rho}{\partial t} = -A\rho_0 \left(\frac{\rho - \rho_f}{\rho_0} \right)^n \exp\left(-\frac{E_a}{RT} \right)$$

A, pre-exponential factor [1/s]; Ea, activation energy [J/mole];
ρ_0 and ρ_f, initial and final densities of the composite [Kg/m^3];
n, order of decomposition reaction

Resin Design for Fire Safety Requirements

Project Number: WVU-1

Boundary conditions

Initial condition: $T(x,t) = T_0,\ \rho = \rho_0,\ \dot{m}_g = 0$

On the hot surface (x=0): $T = f(t)$

On the cold surface (x=L): $\frac{\partial T}{\partial x} = 0,\ \dot{m}_g = 0$

Resin Design for Fire Safety Requirements
Project Number: WVU-1

Assumptions:

- No contraction or expansion during process of heating and decomposition
- No accumulation of volatile gases, i.e., no resistance to gas diffusion
- Thermal equilibrium between the volatile gases and solid material
- No fiber decomposition (temperature$\leq$1000°C)

Material [glass fiber (45 vol. % or 63.6 wt. %) + polyester resin] properties

Property	Value
A, pre-exponential factor [1/s]	1000
Cp_{fr}, fiber specific heat capacity [J/(kg.K)]	760
Cp_r, resin (matrix) specific heat capacity [J/(kg.K)]	1600
Cp_g, gas specific heat capacity [J/(kg.K)]	2386.5
Ea, activation energy [J/mole]	5E+4
k_{fr}, fiber thermal conductivity [W/(m.K)]	1.04
k_r, resin conductivity [W/(m.K)]	0.20
Q, heat of decomposition [J/kg]	-2.3446E+5
R, gas constant [J/(mole.K)]	8.314
T_0, initial temperature [°C]	20
V_{fr}, fiber volume fraction [-]	0.45
ρ_{fr}, fiber density [Kg/m^3]	2560
ρ_r, resin density [Kg/m^3]	1200
ρ_0, initial density of the composite [Kg/m^3]	1812
n, order of the decomposition reaction [-]	1

From Looyeh et al. (1997), Int. J. Numer. Methods Heat Fluid Flow, 7(6):609-625

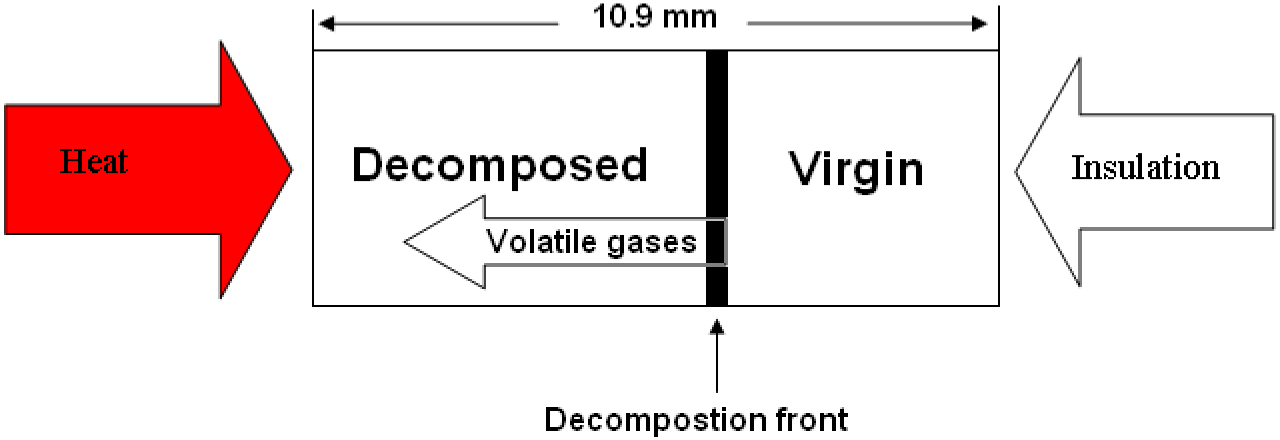
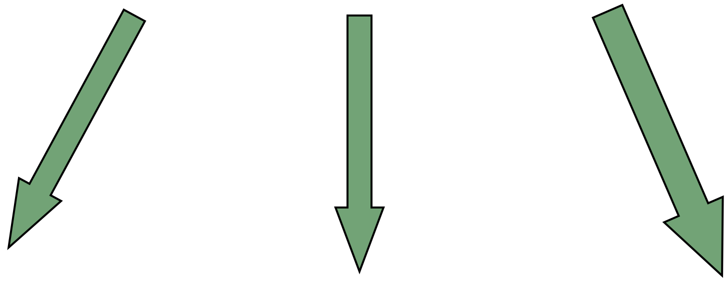


Figure 2. Schematic of the decomposition process in the through-thickness direction

Properties during decomposition

Material in three stages



Undecomposed (virgin) | Decomposing | Decomposed

Degree of decomposition, remain fraction: F

$$F = \frac{\rho - \rho_f}{\rho_0 - \rho_f} \qquad \left[F = 1 \left(\rho = \rho_0\right); \; F = 0 \left(\rho = \rho_f\right) \right]$$

Mixture law

$$k = F k_0 + \left(1 - F\right) k_f$$

$$C_p = F C_{p0} + \left(1 - F\right) C_{pf}$$

Results and discussion

$$\frac{1}{k_0} = \frac{V_{fr}}{k_{fr}} + \frac{1-V_{fr}}{k_r}, k_0 = 0.3142\,[W/(m.K)]$$

$$k_f = \frac{k_{fr}}{1-V_{fr} + \left(k_{air}/k_{fr}V_{fr} + 4\sigma T^3 L/k_{fr}\right)^{-1}} = 0.15855\left[W/(m.K)\right]$$

k_{air}=0.033 [W/(m.K)] evaluated at T=400K, σ=5.67E-8 [W/(m^2.K^4)], L=1.09E-2 [m]

$$\frac{1}{C_{p0}} = \frac{V_{fr}}{C_{pfr}} + \frac{1-V_{fr}}{C_{pr}}, C_{p0} = 1068.5413\,[J/(kg.K)]$$

$$\frac{1}{C_{pf}} = \frac{V_{fr}}{C_{pfr}} + \frac{1-V_{fr}}{C_{pair}}, C_{pf} = 881.0208\,[J/(kg.K)]$$

$$h_g \approx C_{pg}T$$

$$h \approx C_p T$$

Krysl et al. (2004), Int. J. Numer. Methods Eng., 61:49-68

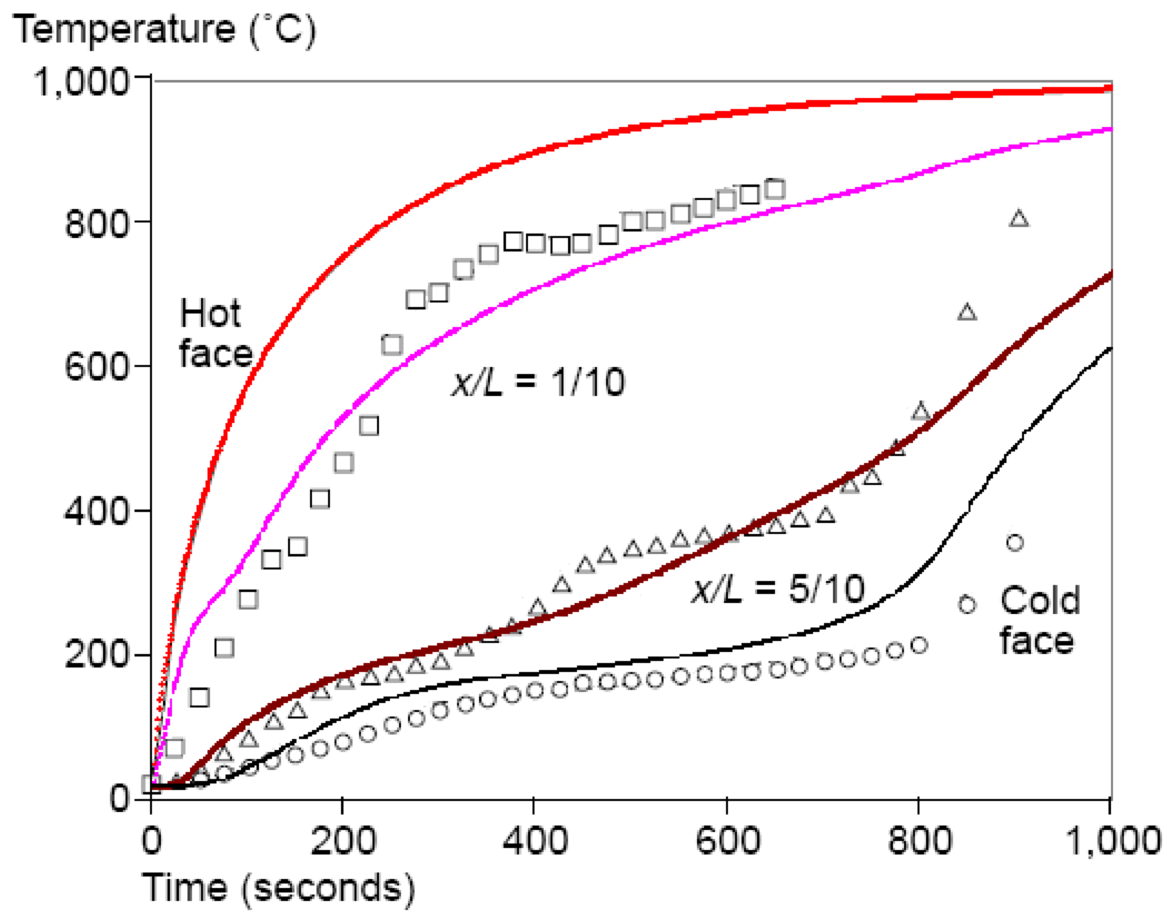


Figure 3. Comparison of temperature between calculations and experiments (Looyeh et al., 1997) at different locations

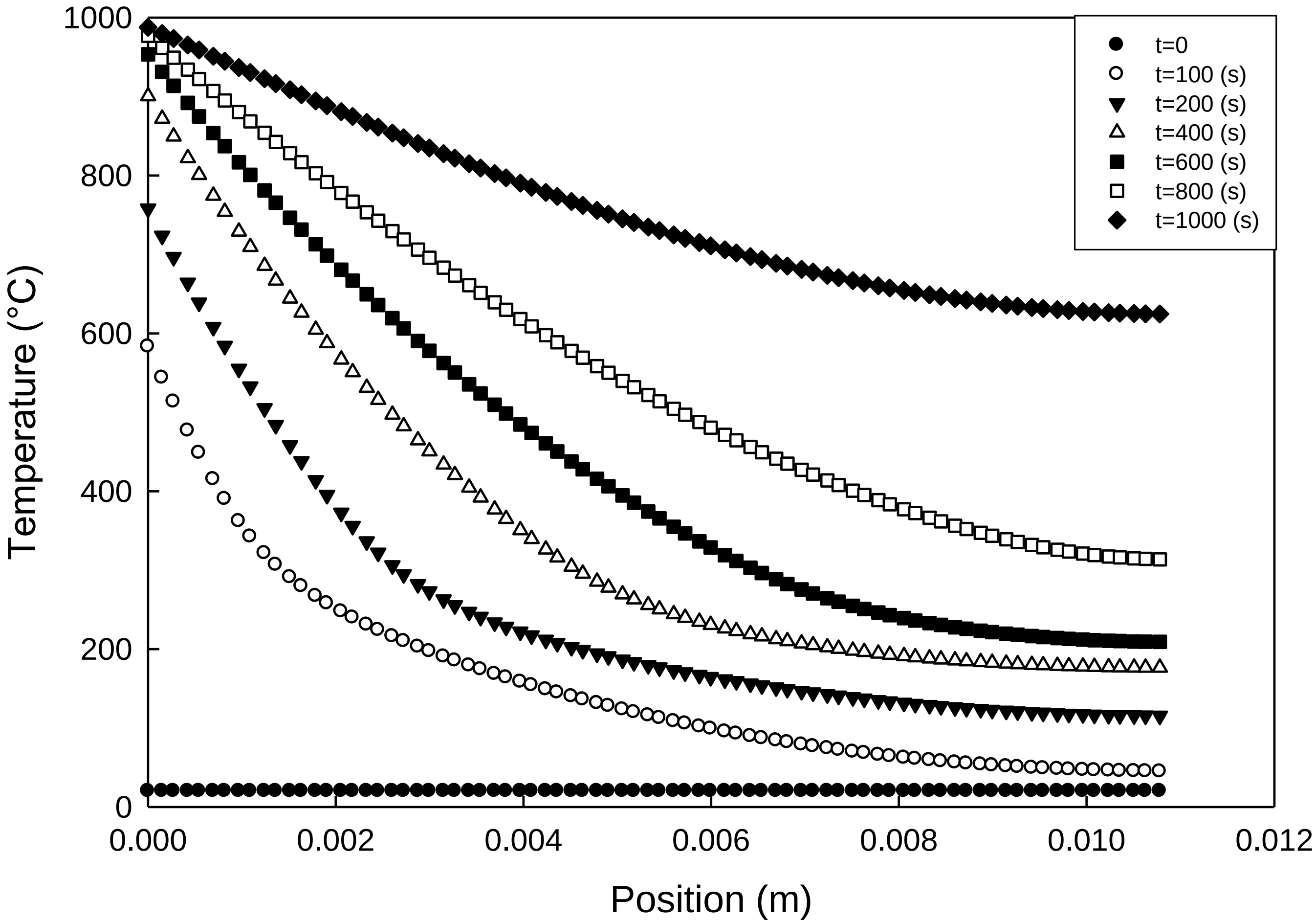
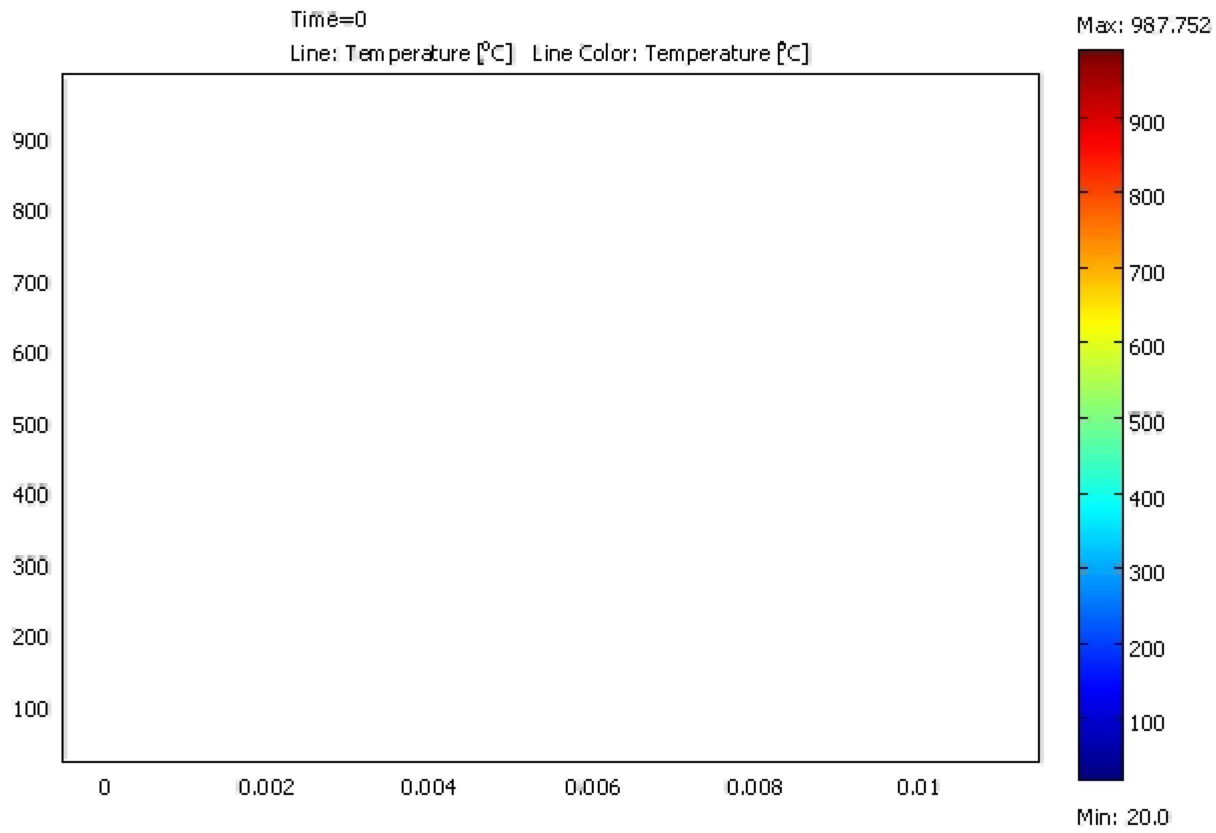


Figure 4. Temperature evolution in the composite



Animation: Temperature evolution in the composite with time

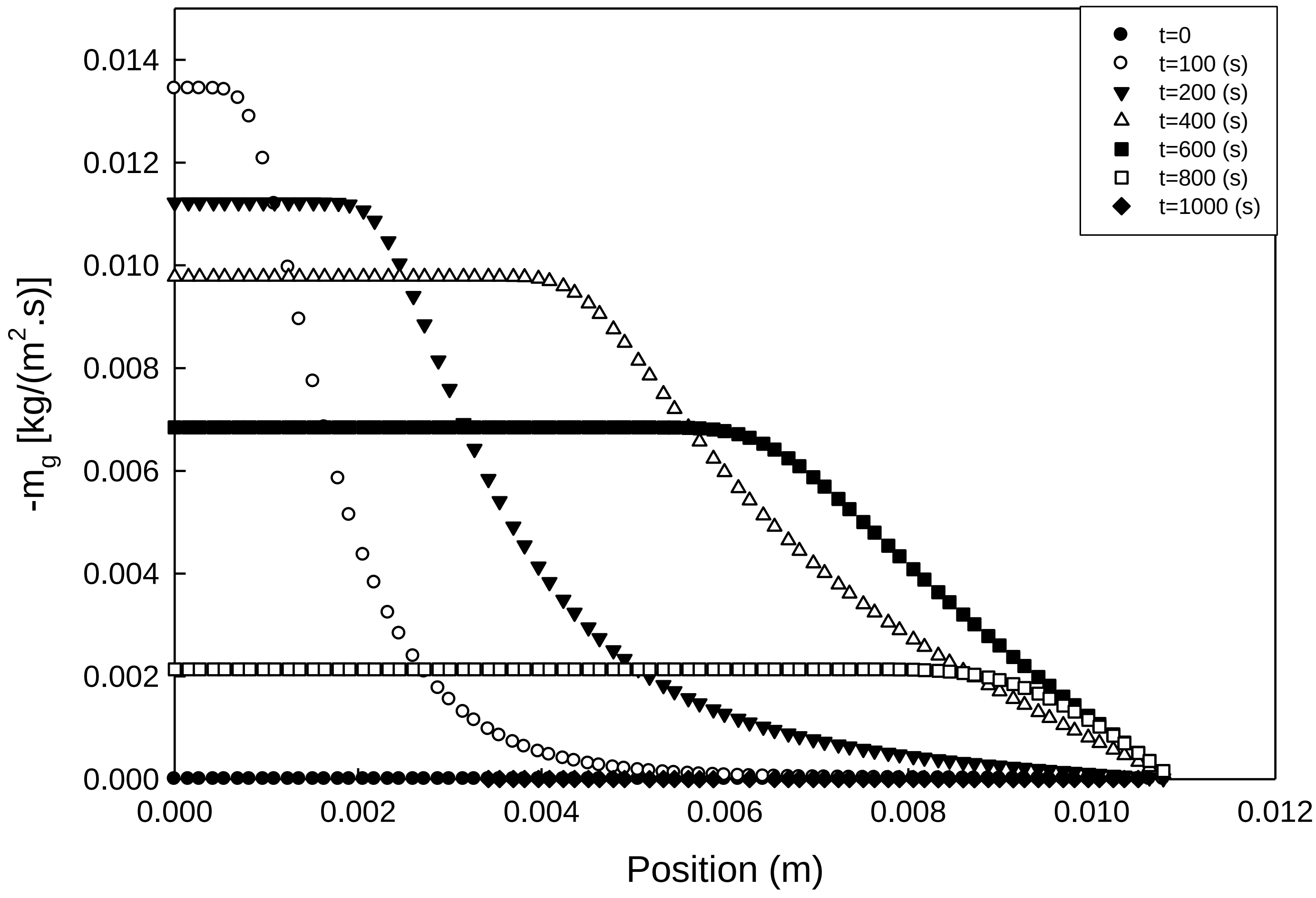
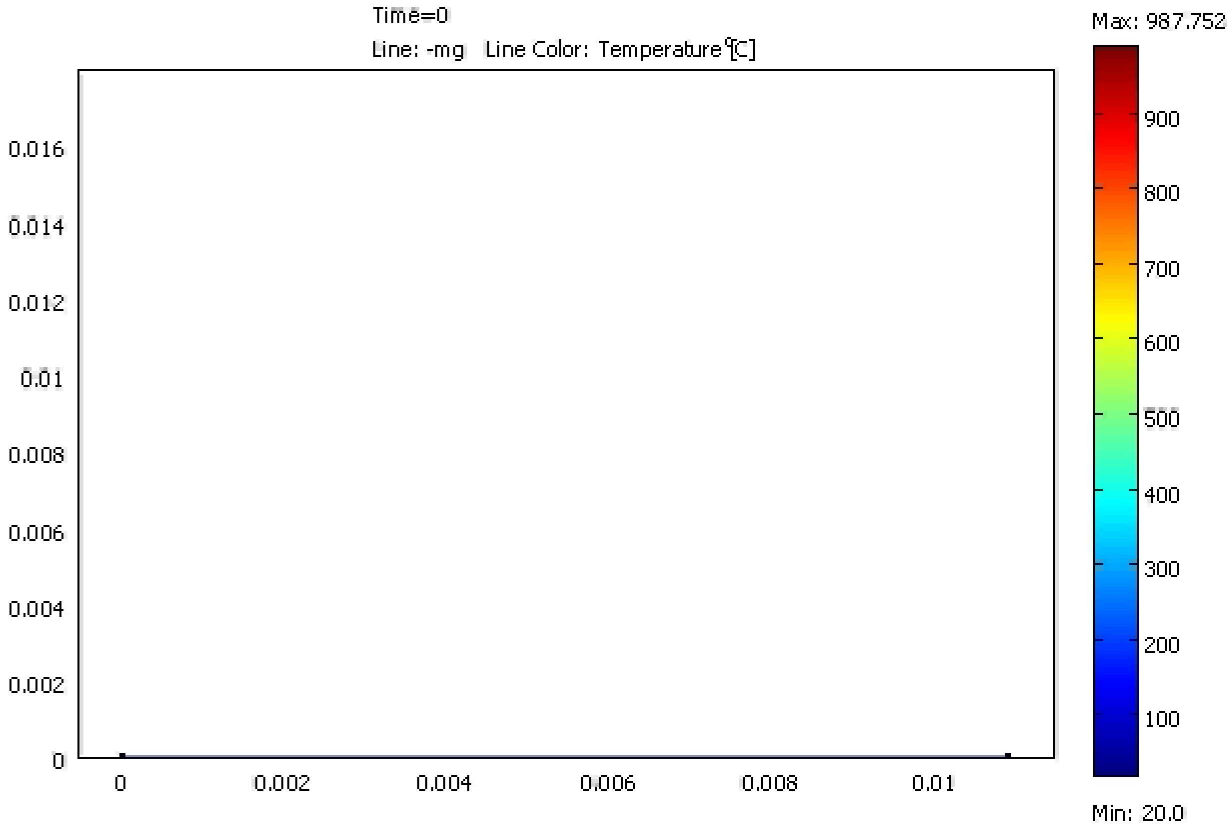


Figure 5. Gases mass flux evolution in the composite

Note that the plateau region at the left of the curve result from no diffusion resistance, while the gradient at the right come from the decomposition instead of diffusion.



Animation: Gases mass flux evolution in the composite with time

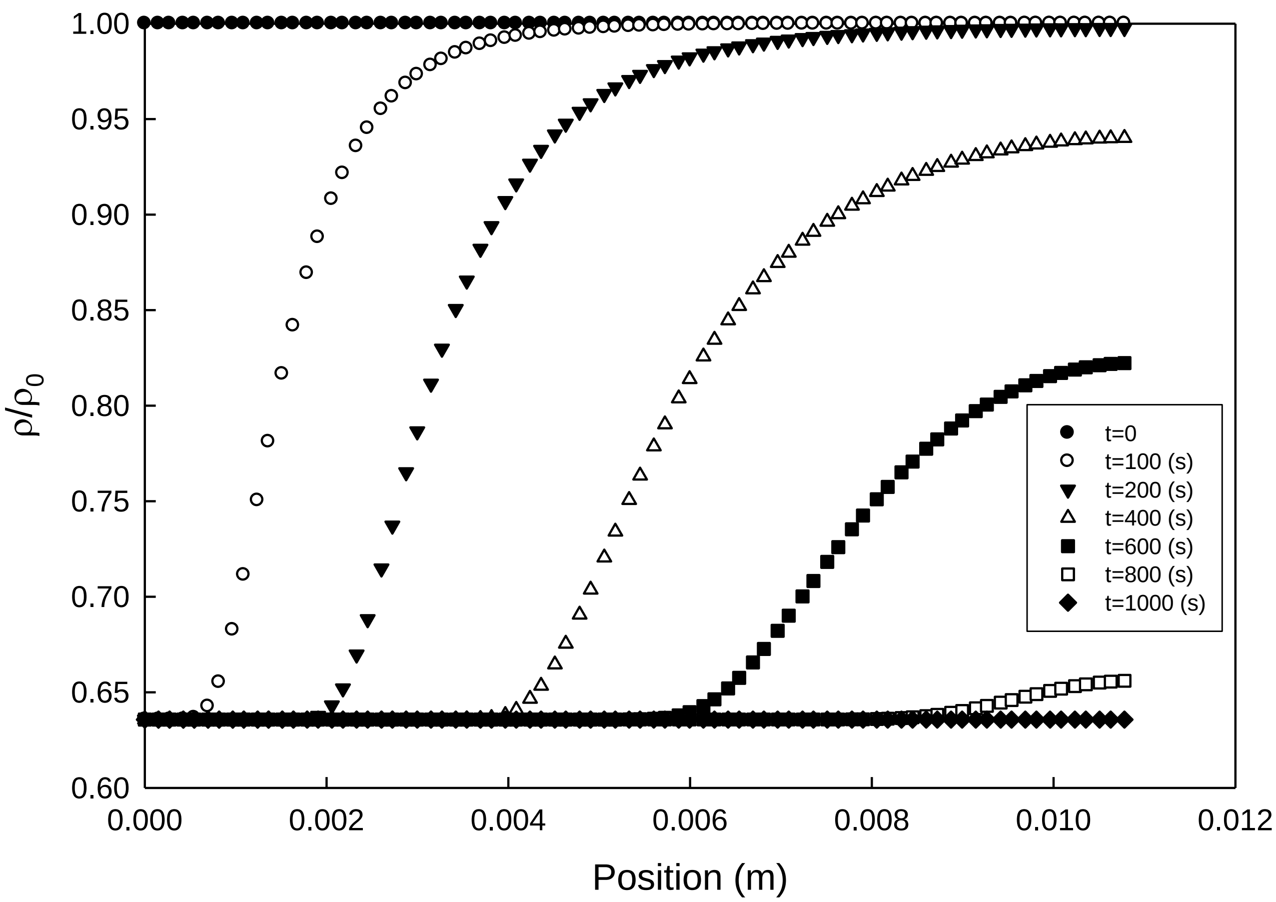
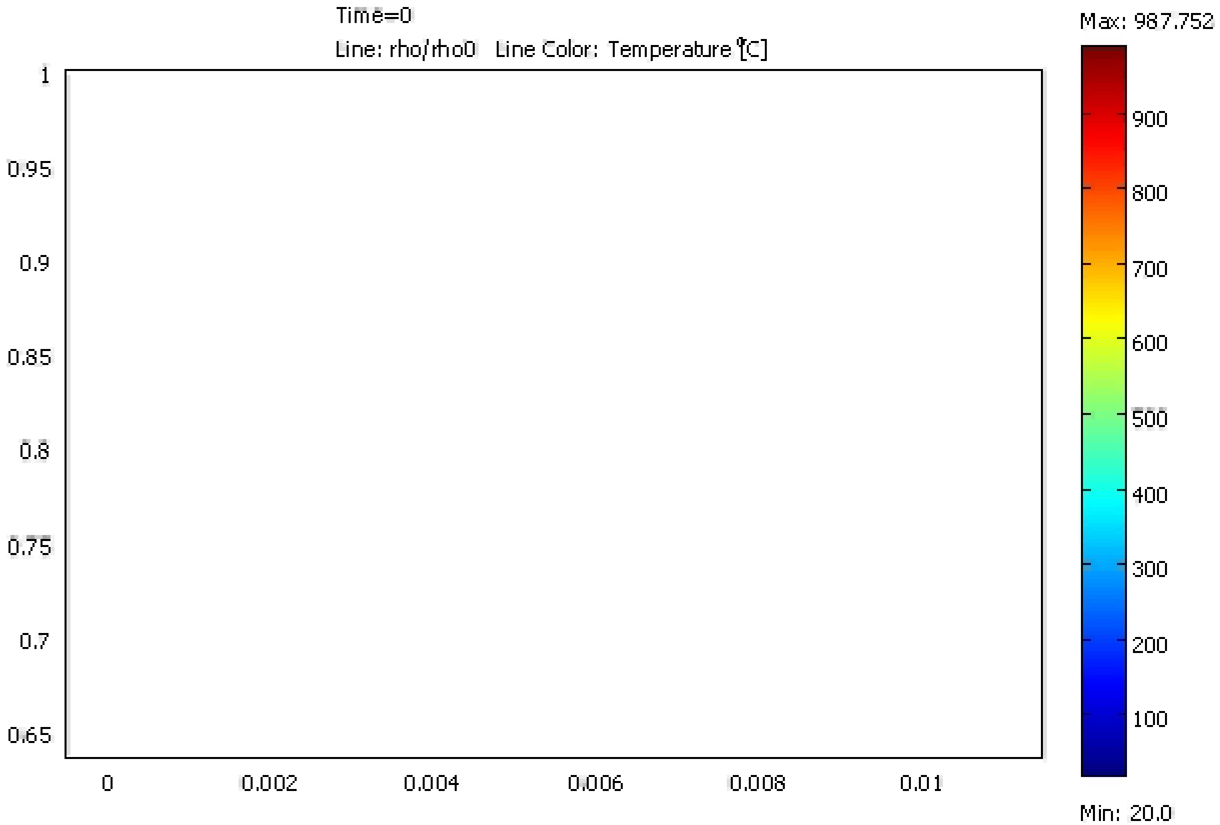


Figure 6. Normalized density of comparison profile in the composite



Animation: Normalized density evolution in the composite with time

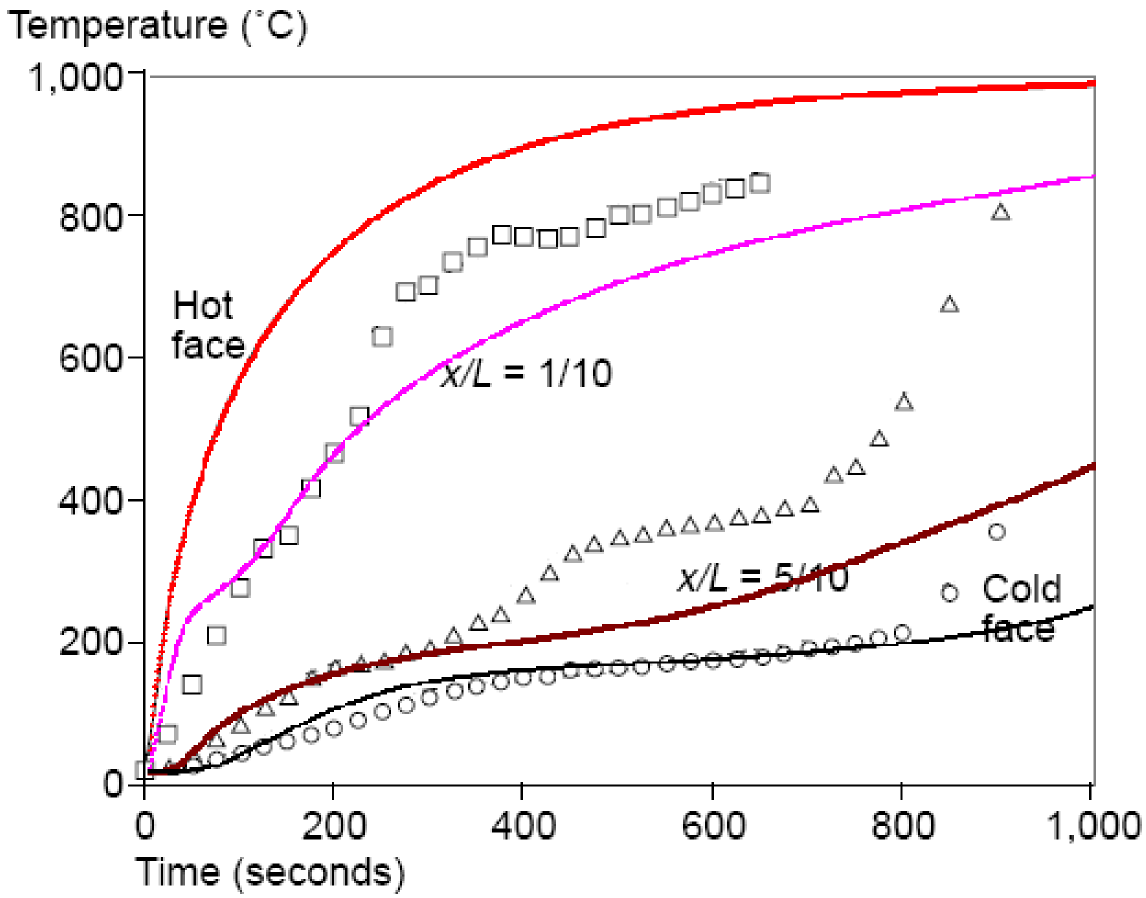


Figure 7. Comparison of calculations (k_f=0.1[W/(m.K)]) and experiments at different locations

Conclusions

- Calculated temperature profiles show reasonable agreement with experimental data
- The model can capture the physics of FRP composite decomposition
- Parameters appearing in the equations need to be determined with accuracy as they play a critical role in predicting thermal behavior

Resin Design for Fire Safety Requirements

Project Number: WVU-1

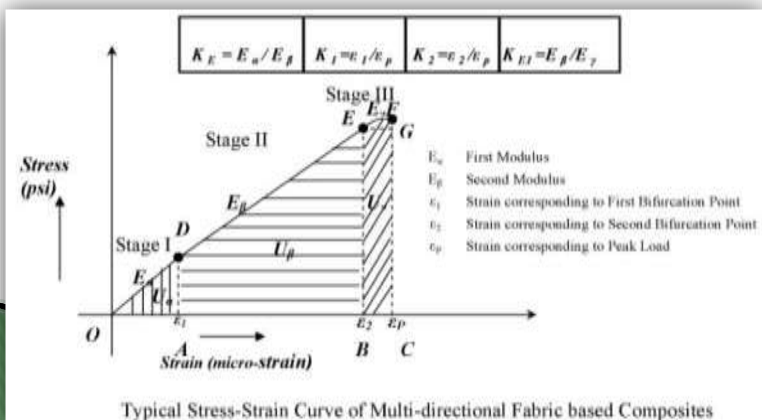
Future Work

- Incorporate temperature-dependent material properties in the model
- Examine influence of charring
- Compute smoke generation and fire spread
- Consider how FRs can delay polymer decomposition and reduce smoke generation and fire spread
- Redo calculations for a load-bearing structure
- Predict mechanical properties, collapse loads and time to collapse

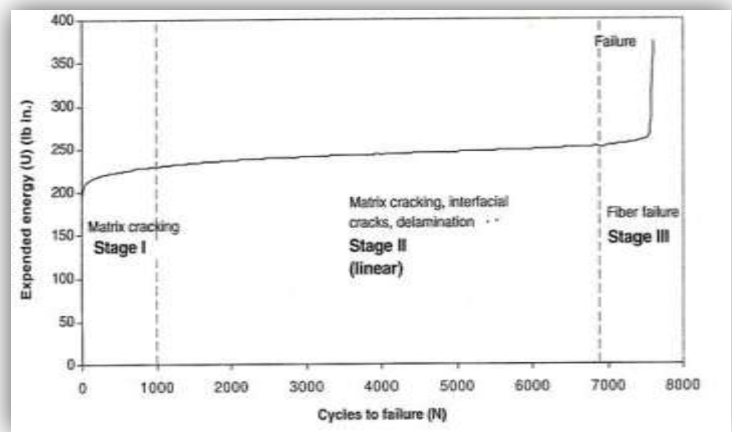
Strength and Fatigue Life Prediction

Project Number: WVU-2

- Project Manager / PI: Hota V. S. GangaRao
- Overview
  - The use of strain energy release rate as the damage metric for a composite material provides easy methods for predicting both the ultimate strength and fatigue life of a material from material properties and loading conditions. Modifications for environmental effects will extend the usefulness of the model to more diverse applications.



Typical Stress-Strain Curve of Multi-directional Fabric based Composites



Strength and Fatigue Life Prediction

Project Number: WVU-2

- Previously Reported Progress
  - Strength prediction
    - Applied to GFRP coupons of various fiber architectures in either tension or bending
    - Applied to different cross sections of full-length columns in axial compression

Strain energy density formula with coefficients from stress-strain curve

$$C = E_\alpha^2 \varepsilon_p^2 \left(\frac{1}{2} K_1^2 + \frac{1}{2} \left(\frac{K_2 - K_1}{K_{E1}} \right) \left(2K_1 + \frac{(K_2 - K_1)}{K_{E1}} \right) + \left(\frac{1 - K_2}{K_{E1} K_{E2}} \right) \left(K_1 + \frac{(K_2 - K_1)}{K_{E1}} \right) \right)$$

Strength and Fatigue Life Prediction

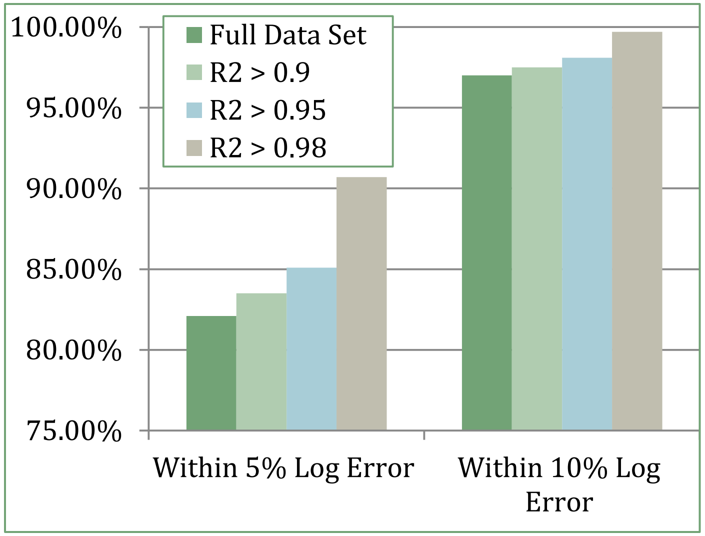
Project Number: WVU-2

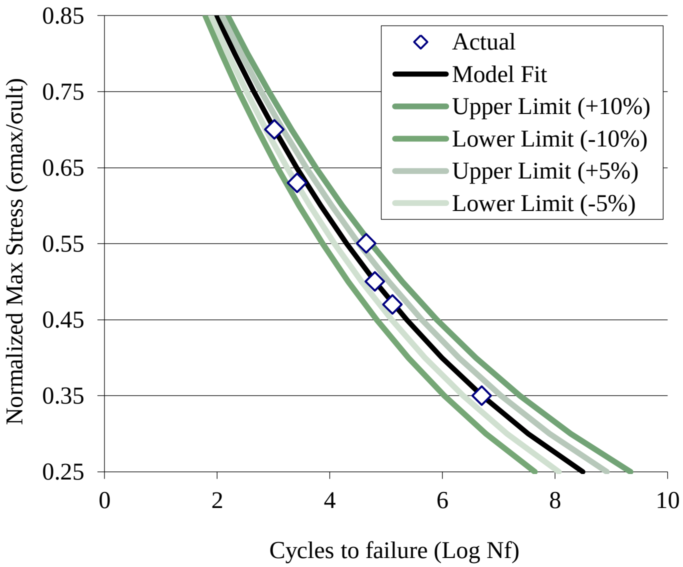
- Previously Reported Progress
  - Strength prediction
    - Accounted for combined loading due to eccentricities in testing
    - Able to predict the failure load to within about 10% of the experimental value

Strength and Fatigue Life Prediction

Project Number: WVU-2

- Previously Reported Progress
  - Fatigue Life Prediction
    - Able to fit and predict GFRP coupon fatigue life data to within 5% log error with over 80% success rate when 3 or more experimental data points were used
    - GFRP beam fatigue lives were also predicted to within 2.5% log error





Strength and Fatigue Life Prediction

Project Number: WVU-2

- Previously Reported Progress
  - Environment Effect on Fatigue
    - Focused on effects of: elevated temperatures, sea water environment, pressurized immersion conditioning
    - Elevating the testing temperature appeared to have an inverse, linear relationship with the fatigue life
    - Presence of sea water caused a 50% decrease in fatigue life depending on exposure time

    - Immersion conditioning at room temperature resulted in a decrease in fatigue life to about 50-65% of the original value, while immersion conditioning at 100°F resulted in a decrease to about 15-25%

Strength and Fatigue Life Prediction

Project Number: WVU-2

- Recent Work
  - Fatigue Life Prediction
    - Strain energy fatigue model compared to a bending fatigue model proposed for the Pre-standard for LRFD of FRP Structures by ASCE.
    - WVU model resulted in fatigue life prediction factor of safety of around 5; ultra-conservative pre-standard model resulted in factor of around 100.

Original WVU Equation:

$$N_f = \frac{U_o}{2(\frac{dU}{dN})} = \frac{U_o}{2\left(a\left(\frac{\sigma_{max}}{\sigma_{ult}}\right)^b\right)}$$

WVU Equation modified for comparison to pre-standard:

$$\Delta S = \left(\frac{(\sigma_{ult})^2 IL}{48c^2 EaN}\right)^{\frac{1}{m}}$$

Strength and Fatigue Life Prediction

Project Number: WVU-2

- Future Work / Conclusion
  - Obtain fatigue data from more sources, continue to try to establish good model constants
  - Sample properties and testing conditions need to be explored and incorporated into the model constants
  - Environmental effects may be able to be incorporated into the life prediction model as factors
  - Additional GRFP column strength testing planned for Bedford Reinforced Plastics (after aging in wet and high temperature environments)
  - Additional GRFP coupon fatigue testing planned for Lockheed Martin (focusing on effect of seawater aging)



LIFE Form Completion

Aging testing and analysis of composites
Project Number: WVU-3

- Project manager / PI: Liang, Vijay and Hota
- Overview
  - **Objectives:**
    - to create database from accelerated lab test data and field test data
    - to develop predictive models for the durability of composites over a range of chemo-thermo-mechanical environments including knock-down factors
  - **Approach:**
    - Generate new data on materials and test type as per IAB specification
      - Natural composites vs. GFRP
    - Synthesize existing durability data from literature and other researchers
  - **Scope of work:**
    - Standardize aging test protocol for industry acceptance
      (We need an ASTM Standard Practice for Accelerated Aging of Composites)
    - Evaluate mechanical properties under varying environmental conditions
    - Correlate accelerated lab data to field (natural) weathering data
    - Evaluate the data with existing models and develop new model(s)
- Budget update: $40k per year for three years

Aging testing and analysis of composites
Project Number: WVU-3

- Progress to date
  - Review and analysis of new aging data of GFRP composites under accelerated and in-service conditions, including evaluation of time-temperature superposition method for performance prediction
  - Development and collection of natural fiber/resin composites and planning of their aging studies including test matrix
  - Review Technical Paper "Natural Fiber Reinforced Pultruded Composites" by Bhyrav Mutnuri of Bedford Reinforced Plastics Inc
  - Receipt of test samples for long term performance evaluation for deep seawater application (including void, post cure, knitline effects) and full spectrum of testing being started
  - Continuation of collection of long term sorption test data
  - Aging tests (temperature related) on natural FRP composite coupons and axial testing of GFRP column specimens (3”x3”x72”)

Aging testing and analysis of composites
Project Number: WVU-3

- **Aging studies of sustainable plant-based biocomposites**

- to be conducted under a variety of conditioning environments
- both static bending and tension tests at coupon level
- correlation of accelerated aging to natural aging if field aged samples are available
- to establish if strength and stiffness properties of the natural composites would experience any significant reduction and compare with GFRP data under the same aging conditions

Parameters to be considered include:

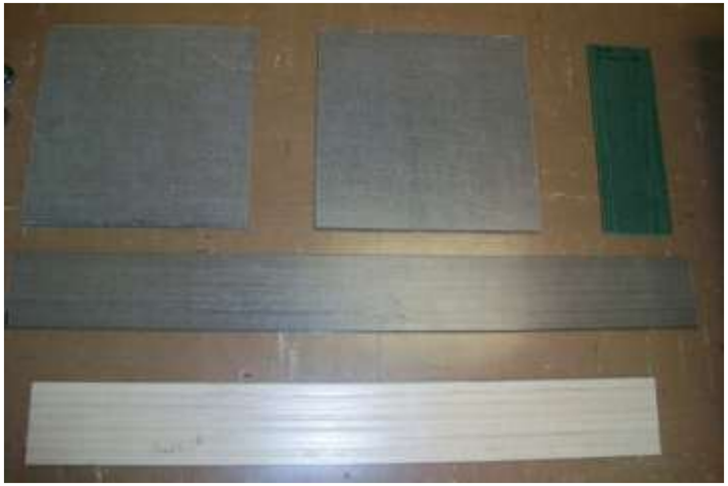
1) form and quality of natural fibers (current focus is on flax)
2) fiber/resin chemical bonding (compatibility, sizing)
3) fiber content
4) void content
5) moisture absorption
6) resin type
7) manufacturing method

Parameter	**DRY CONDITION**
Fiber Type	Glass and Natural fibers (flax)
Resin Type	Vinylester, Phenolic, Envirez (Ashland Chem.)
Specimen Type (Number of Specimens)	Column (box) sections (3”x3”x6 ft.)- 24 specimens Rectangular flat specimens (1/2”x0.25”x10”) - 90 specimens
Replications	3 each
Temperature (^{o}F)	32, 70, 100, 150
Immersion	Dry, Wet
Aging Duration (days)	1, 15, 60, 180, 360
Testing Type (ASTM)	Tension and bending

Aging testing and analysis of composites

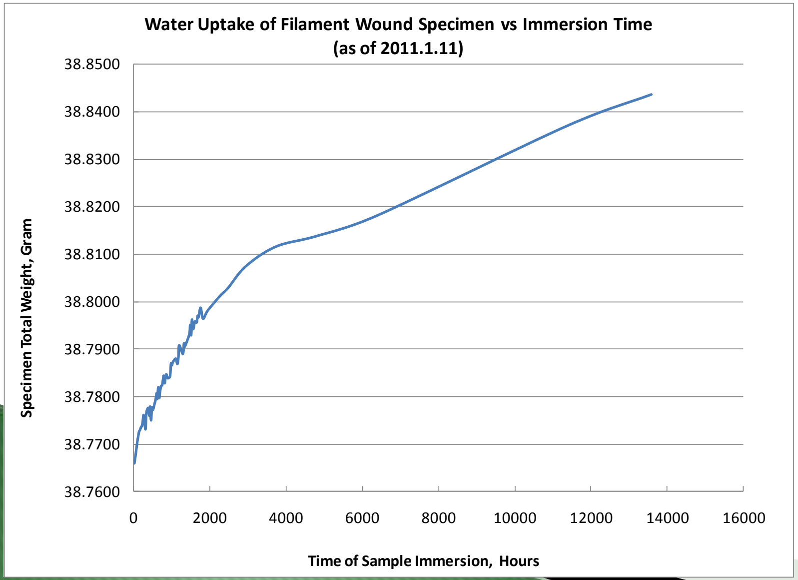
Project Number: WVU-3

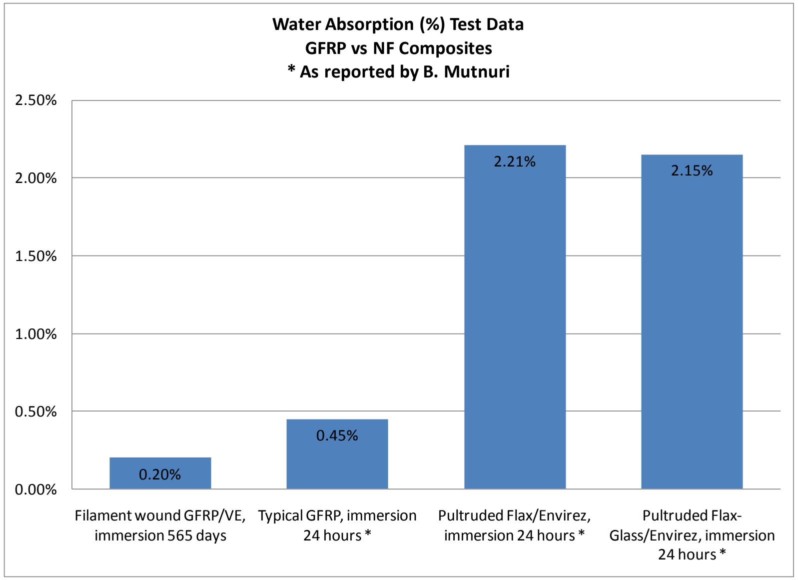
- **Aging studies of sustainable plant-based biocomposites**



The following samples are being used for aging studies as part of CICI IAB selected project:

- GFRP with VE
- GFRP/ENVIREZ 50380 Ashland resin
- High Density Flax/ENVIREZ 70301 Resin
- Medium Density Flax/ENVIREZ 70301 Resin



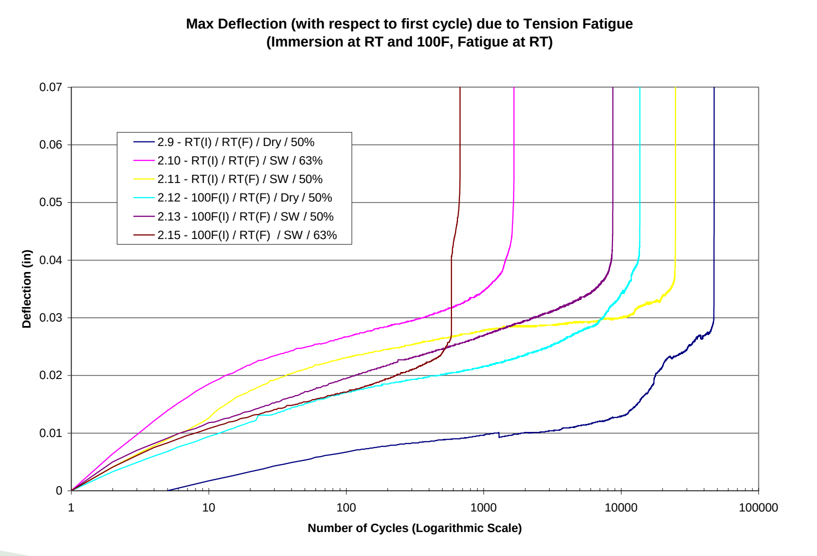


Aging testing and analysis of composites

Project Number: WVU-3

- **Aging effects on tension fatigue life of VARTM based GFRP composites**

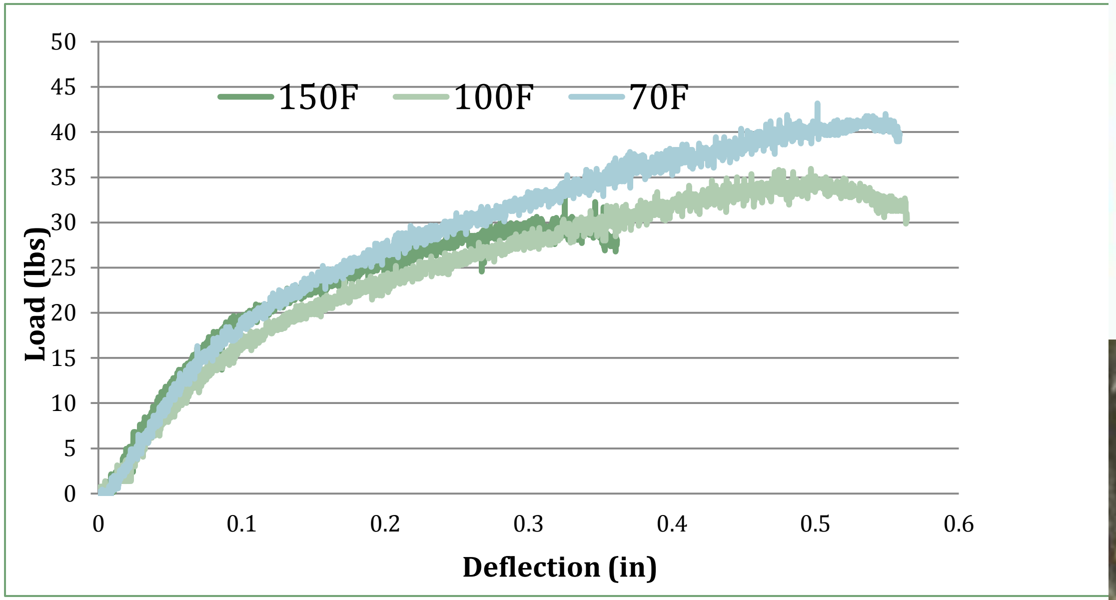
- Test samples received Dec 28, 2010
- Static tests are being conducted
- Full spectrum of tension-tension fatigue will begin soon
- Material parameters considered including
    - Void content
    - Post cure
    - Knitline (joint from mold to another)
- Testing parameters considered including
    - Baseline fatigue data (testing at dry and without aging)
    - High pressure seawater aging
    - Testing under seawater immersion
    - Varying fatigue stress level



Aging testing and analysis of composites

Project Number: WVU-3

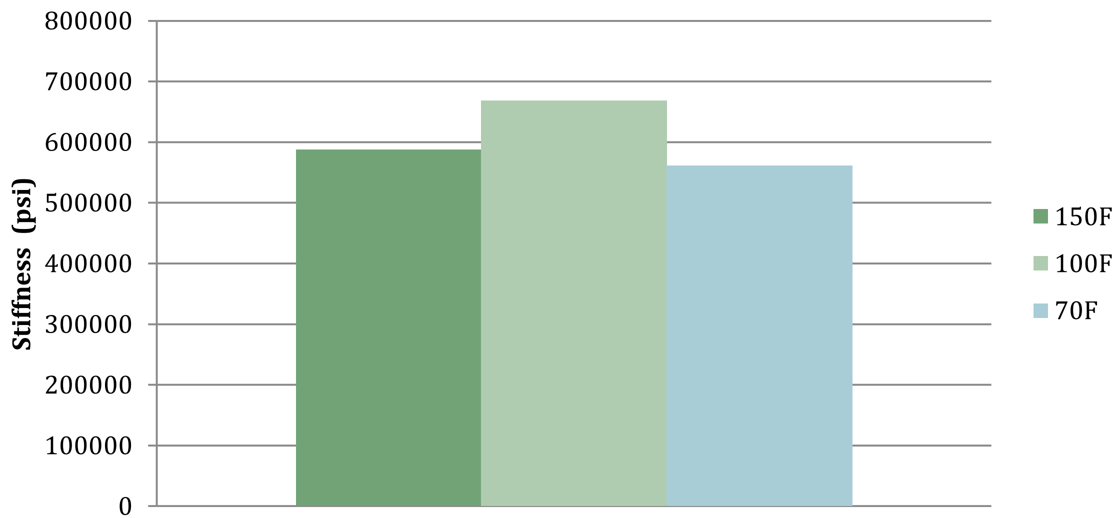
Temperature related load vs. deflection behavior of natural fiber composites (flax + phenolic resins)



Aging testing and analysis of composites

Project Number: WVU-3

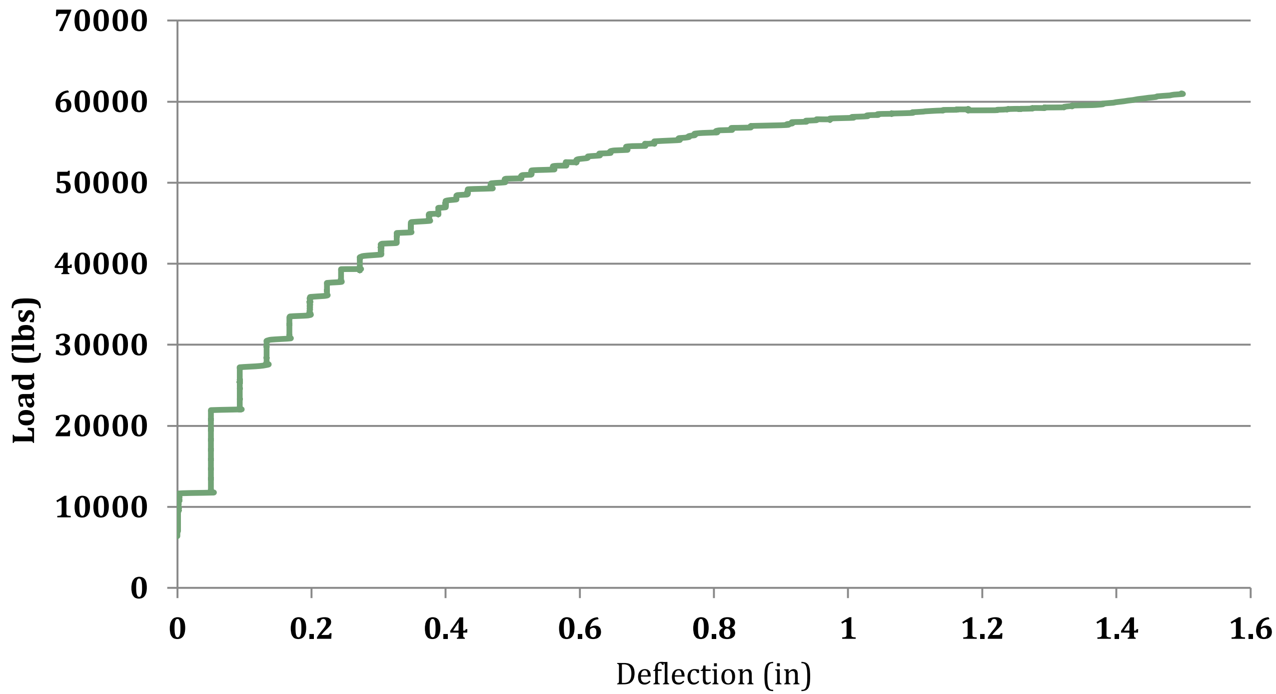
Stiffness variation of natural FRP composites (flax + phenolic resin) with temperature



Average (E) at 150 ^{0}F, 100 ^{0}F and 70 ^{0}F for Natural FRP coupons were 0.59×10^6 psi, 0.67×10^6 psi and 0.56×10^6 psi, respectively

Aging testing and analysis of composites
Project Number: WVU-3

Typical Load Vs Deflection Curve For 3"x3"x72" GFRP Columns
(Note: Preliminary Tests are Conducted and Aging Tests will Follow)



Aging testing and analysis of composites
Project Number: WVU-3

- **Ongoing work**
  - To conduct aging studies of natural fiber/resin composites at coupon level and compare their data to those of GFRP with reference to their potential applications for energy efficient buildings
  - To conduct tension-tension fatigue tests to assess the salt-water fatigue behavior of FRP composites to arrive at safety (knock-down) factors for GFRP coupons for applications as specified by industry members
  - Conducting aging studies for tensile and bending properties (dry/wet immersion, temperature variations for up to 360 days)

Aging testing and analysis of composites

Project Number: WVU-3

LIFE Form Completion

Thank you

Some conditioning methods at WVU for aging studies

- High pressure
- High temperature
- Seawater or other liquid immersion

- Boiling water immersion

- Sustained stress
- Alkaline immersion

- Freeze-thaw
- Temperature
- Humidity

- Temperature
- Humidity under testing

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4 (ONGOING)

Project Manager / PI

Udaya B. Halabe, Ph.D., P.E., ASCE Fellow

Professor

West Virginia University

Department of Civil and Environmental Engineering

Morgantown, WV 26506-6103

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Overview:

- Periodic monitoring of the FRP components is necessary for the timely detection of subsurface defects and to ensure continued structural integrity

- Infrared Thermography (IRT) is emerging as a promising nondestructive technique for this application
  - Portable Equipment
  - High speed data acquisition
  - Easy data interpretation

- Examples of subsurface defects that can be detected using IRT
  - Subsurface debonds and delaminations in FRP bridge decks, FRP panels
  - Debonds between FRP wrap and the underlying structural component
  - In-situ evaluation of concrete bridge components prior to rehabilitation using GFRP fabrics

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Past Research at WVU (2000-2009) – supported by FHWA

- **Laboratory investigations on many Glass Fiber Reinforced Polymer (GFRP) composite bridge deck specimens and GFRP fabric wrapped components with embedded debonds and delaminations using digital infrared camera**

  - Debonds are gaps between two dissimilar layers (e.g., wearing surface and underlying deck)

  - Delaminations are defects within the flanges of an FRP deck

On-going Research at WVU (2000-Present) – supported by USDOT-FRA and WVDOH

- **Field infrared testing and evaluation of :**

  - GFRP bridge decks

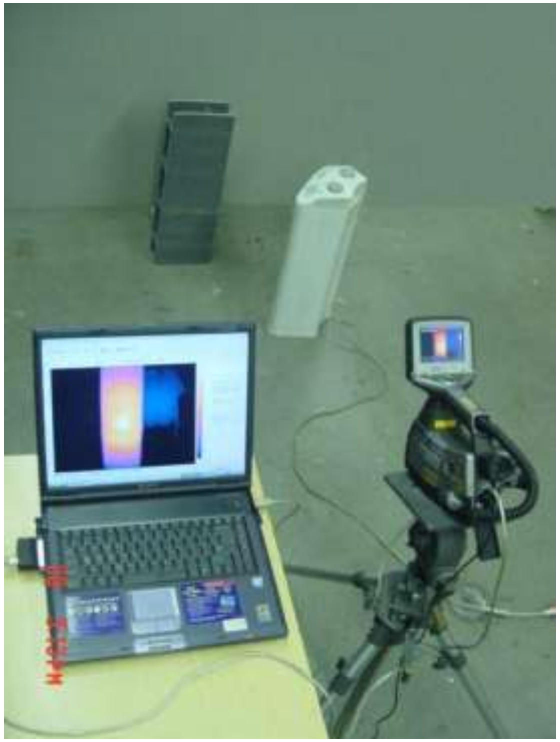
  - GFRP wrapped components in timber railroad bridges

  - Concrete bridge components before & after rehabilitating with GFRP wraps

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

IRT Monitoring System (Thermal Sensitivity 0.06-0.10^{o}C at 30^{o}C)



Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Heating Sources

- Quartz Heater
- Heating Blanket
- Solar Radiation

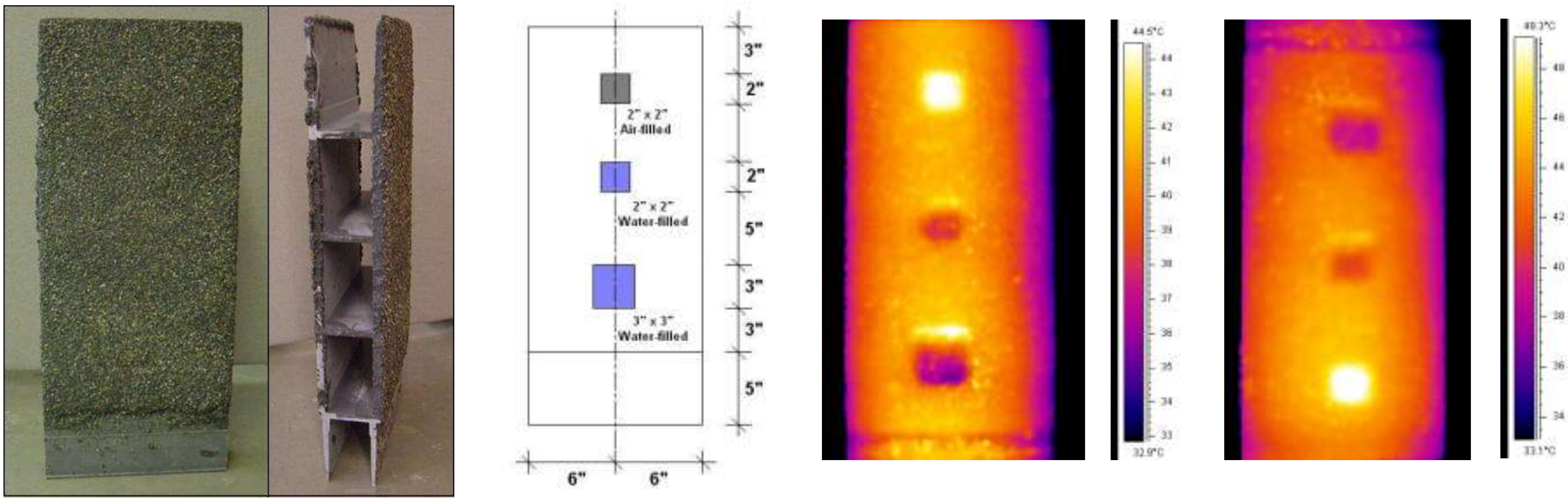
Quartz Heater (1500W capacity)

Heating Blanket (1500W capacity)

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Example of Laboratory Test Results



(a) (b) (c) (d)

(a) Deck specimen BD2 with embedded debonds, (b) Schematic showing debond locations with air-filled debond of size 2” x 2” x 1/16” and
water-filled debonds of sizes 2” x 2” x 1/16” and 3” x 3” x 1/8”
(c) Infrared image of deck BD2, (d) deck BD2 placed in inverted position,

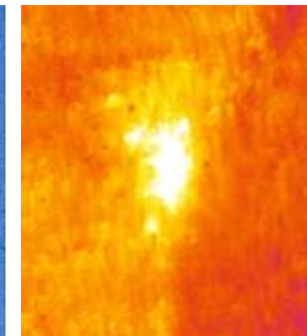
Surface Temperature difference between defect-free and defective areas:
(a) 5.7°C (b) – 2.5°C (c) – 3.9°C

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

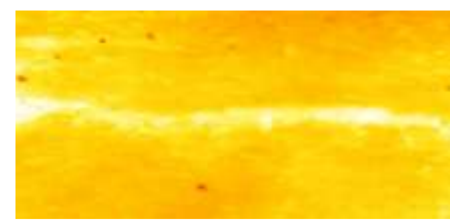
Project Number: WVU-4

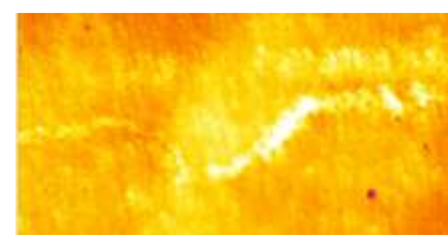
Example of Field Test Results - WVDOH

La Chein FRP Bridge, Monroe County, WV



Photograph and Infrared image of a small debond



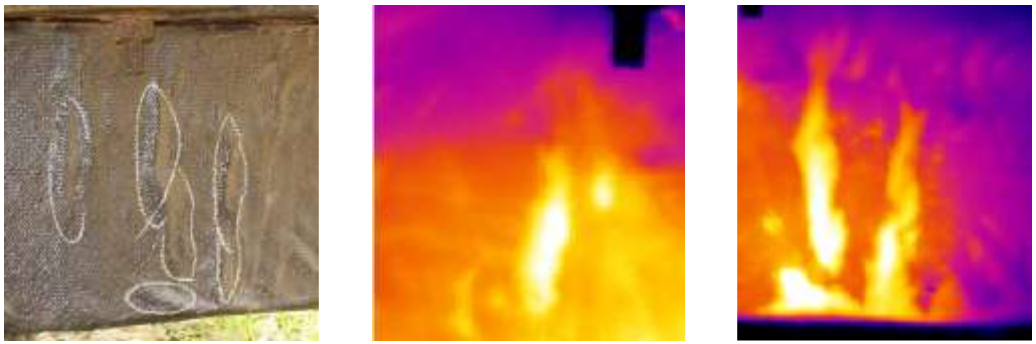


Photograph of a crack in the wearing surface

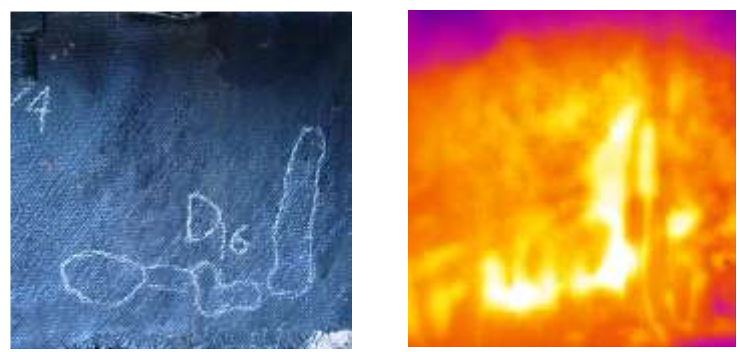
Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Example of Field Test Results – GFRP Wrapped Timber Railroad Components



(a) Photograph of debonds D1, D2, D3 (b) Infrared image of debonds D1 and (c) debonds D2, D3



(a) Photograph of debond D16 (b) Infrared image of debonds D16

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Project Work Plan under CICI

- Investigate the use of Infrared Thermography in an on-line setting for manufacturing quality control.
- Develop guidelines and procedures for application of infrared thermography by field technicians and contractors for construction quality control and periodic monitoring over the service life of the structure, and prepare a comprehensive report/inspection manual with examples (case studies).

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4

Progress Update/Budget to Date (under CICI):

Work Start Date: May 16, 2010

Budget: $40,000 per year (received ~ $20,000 so far)

Recent Activities (May 16, 2010 – present) – under CICI funding:

- **Use of IRT in Bedford Reinforced Plastics (BRP) plant on July 8, 2010.**
- **Literature review and collection of case studies on current IRT applications to composite components.**
- **Infrared testing of a West Virginia concrete bridge (using direct WVDOH funding) prior to rehabilitation using GFRP fabrics**
- **Work has commenced on preparing a comprehensive report/inspection manual on the use of IRT for nondestructive evaluation of FRP composite components in manufacturing and field setting (needed for field inspectors for quality control of initial construction and periodic in-service monitoring).**

Nondestructive Evaluation of FRP Composites Using Infrared Thermography (IRT)

Project Number: WVU-4 - LIFE FORM COMPLETION

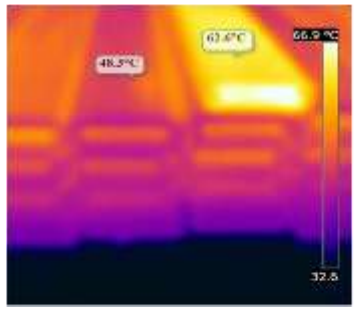



Photo and IRT image of stacked channel sections (Bedford Reinforced Plastics)

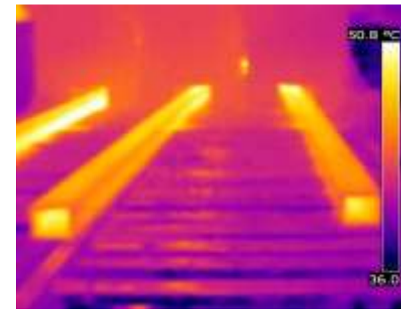



Photo and IRT image of tube sections coming out of the manufacturing die (Bedford Reinforced Plastics)

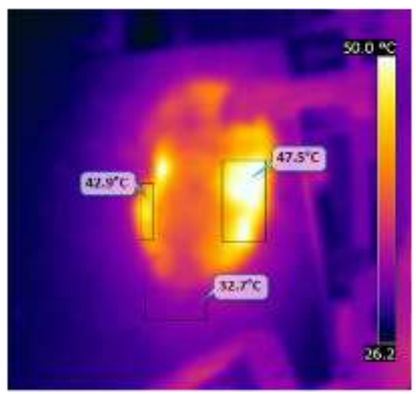
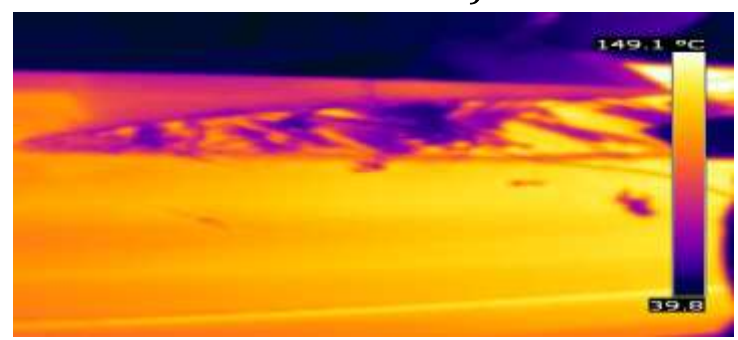



Photo and IRT image of a concrete pier cap that is a candidate for repair using GFRP (WVDOH)



IRT image showing debonding of FRP layer in a pultruded panel during initial set up which was later adjusted to pultrude defect-free panels (Bedford Reinforced Plastics)

Design, Manufacture, and Implementation of Structural PANELS (Shapes)

Project Number: WVU-5

February 1, 2011

P.V. Vijay, Ph.D.

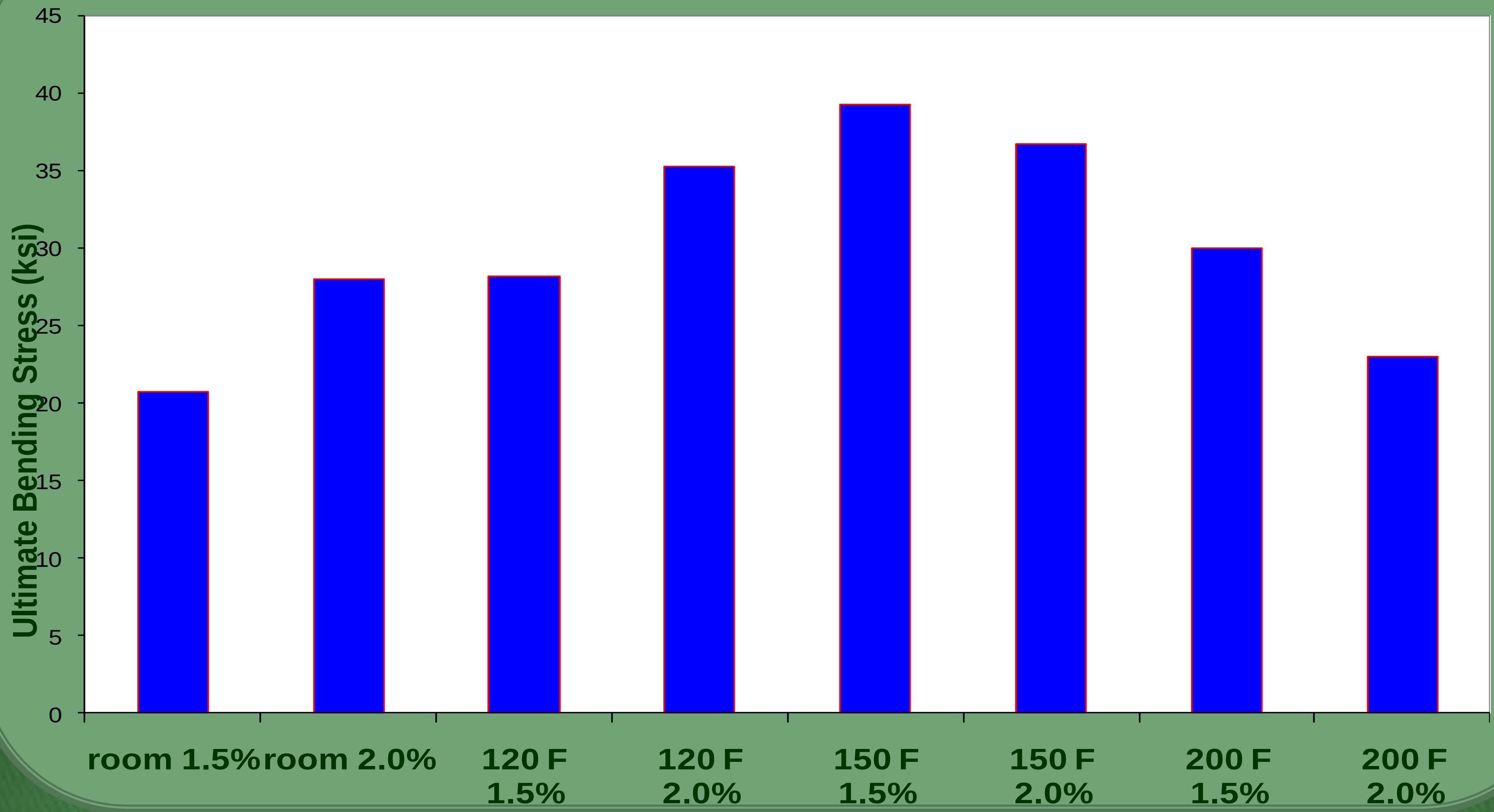
Hota V.S. Gangarao, Ph.D., P.E.

Constructed Facilities Center
West Virginia University

Objectives

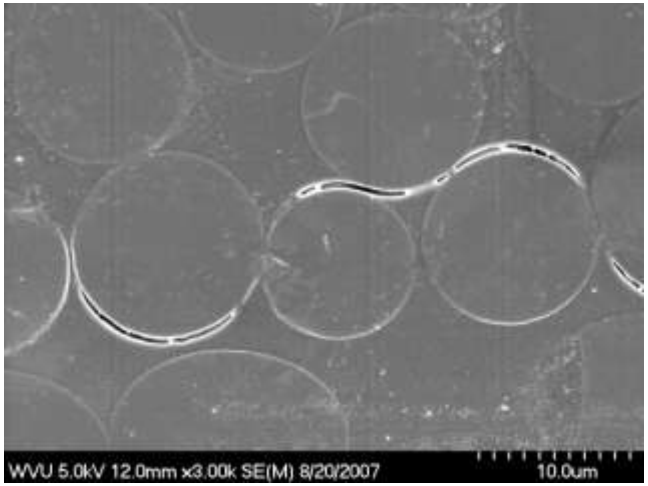
- Design/develop/evaluate modular FRP panels with efficient and cost-effective fiber-fabric architecture & joining schemes under static and fatigue loads.
  - Static: Coupon tests
  - Static: Component bending (stresses/strain/deflections)
  - Fatigue: Stresses/strains, S-N curves
- Theoretically evaluate strength/stiffness of modular panels.
- Experimentally evaluate joining /anchoring schemes
- Assess durability of panels (limited work during first year)

Ultimate Bending Stress (UBS) of coupons

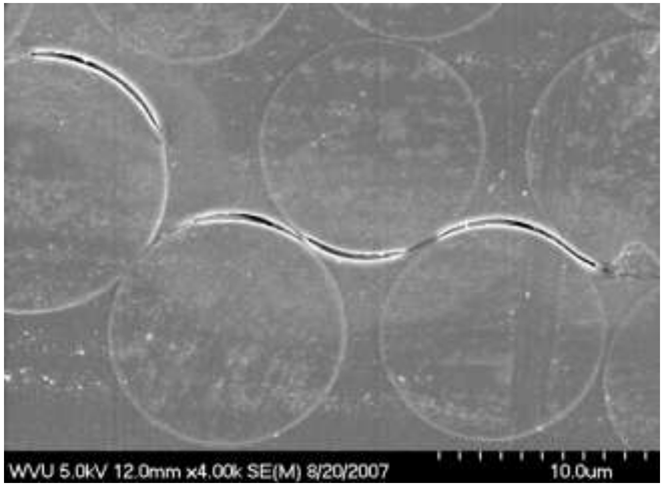


Average Value of UBS is 30 ksi (Difft. Temp. & Catalyst)

Scanning Electron Microscope

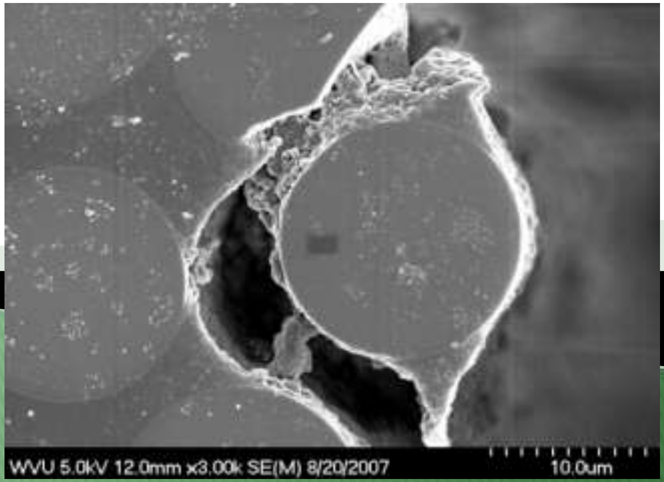


Room temperature and 1.5% Catalyst



Room temperature and 2.0% Catalyst

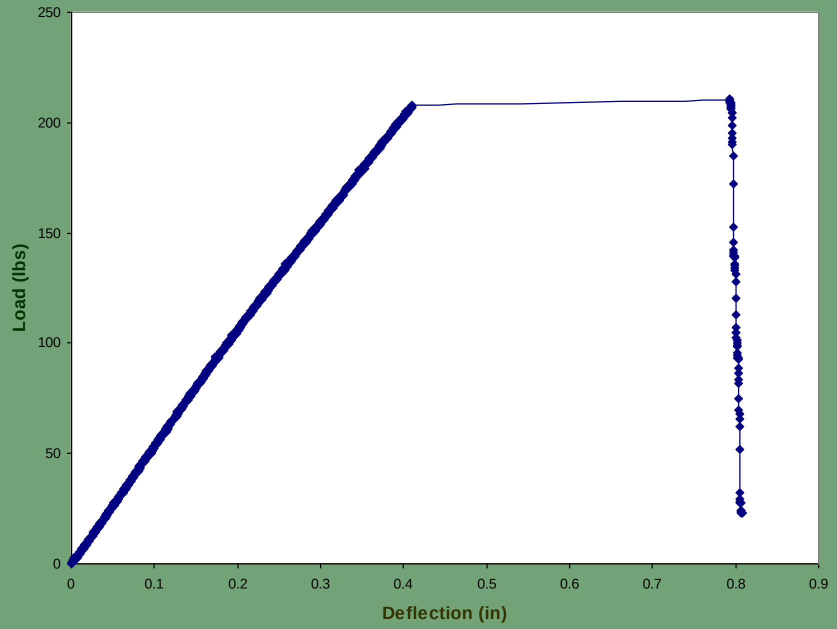
150^0 F with 1.5% and 2% Catalyst

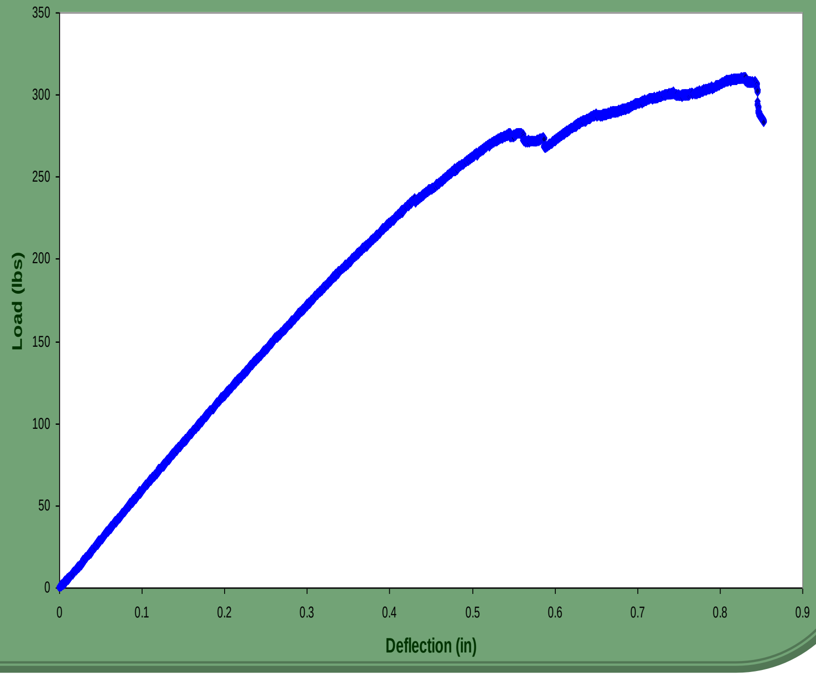


200^0 F with 1.5% Catalyst

Failure Mode & Energy absorption

Load-Deflection Curve





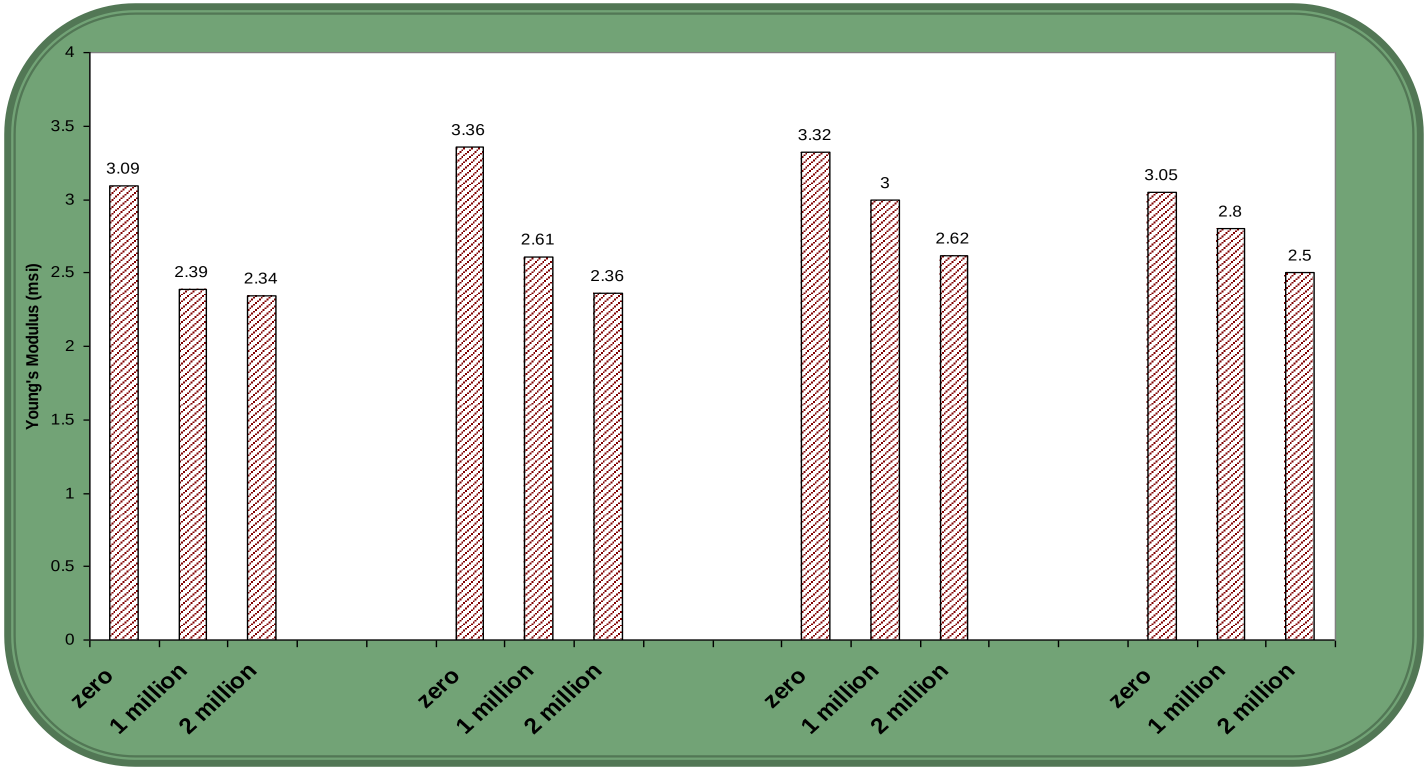
Samples cured at 200^0 F **Samples cured at 150^0 F**

Mechanical Properties of shapes/ Panels

Target Strength/Stiffness Values

- Avg. Fiber Volume Fraction in flanges and webs: ~50%.
- Avg. Ultimate Bending Stress & Modulus: ~55 ksi & 3.5 msi.
- Avg. Ultimate Tensile Stress & Modulus: ~40 ksi & 3.25 msi
- Average Ultimate Shear stress: ~10 ksi.

Mechanical Properties of panel

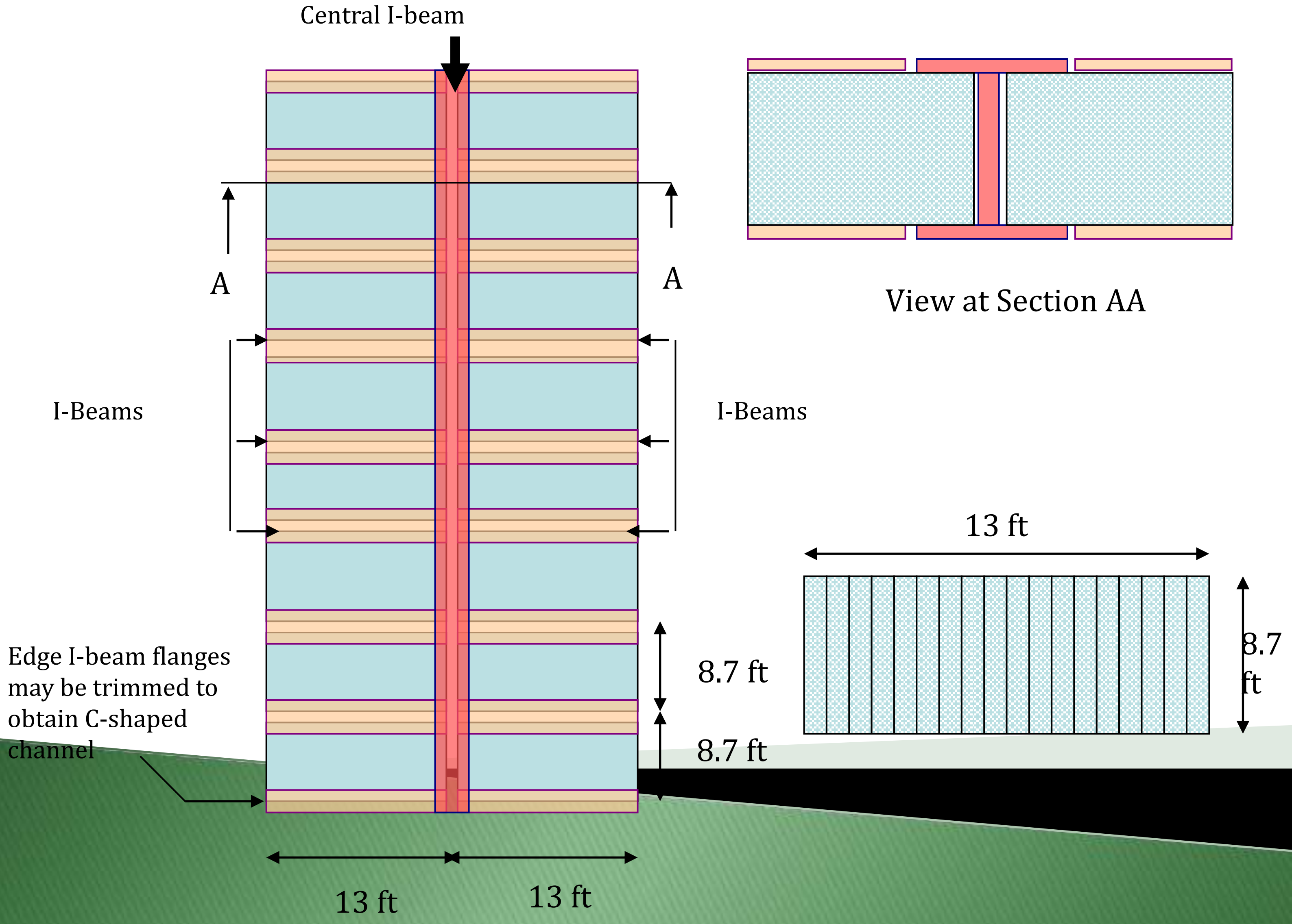


Avg. decrease: 20% after 2 million cycles

Type I Type II Type III Type IV

Bending modulus value of the panel from three point bending test after 'N' cycles (calculated from Load-Deflection data) (Types refer to cell/patch load/panel flip config.)

Field Installation Layout



FILED CONNECTION LAYOUT

Field Monitoring

- **Asphalted FRP panels are performing very well.**
- **Joining schemes with shimmed FRP I-sections and glassing schemes need tight fit without shimming for future installations.**
- **Pavement surface characteristics (ridability, surface cracks, support condition at pavement junctions) have remained practically unchanged over the summer and winter temperatures (freeze-thaw, hot and cold temperatures).**

FUTURE WORK/SUMMARY

- **Coupon results from static and fatigue tests will be evaluated.**
- **Durability tests are beginning to be conducted on coupons from FRP panels/ components (dry and wet conditions with temperatures up to 150 F),**
- **The field installed panels are performing as per the design and the joining schemes require additional modifications and research for proper load transfer.**
- **Design methodology for modular panels is being developed and will be refined with information from additional test/field data.**