Fiber-Reinforced Plastic Bridges

Rakesh K. Gupta and Hota V.S. GangaRao
West Virginia University
Morgantown, WV 26506

Presentation Contents

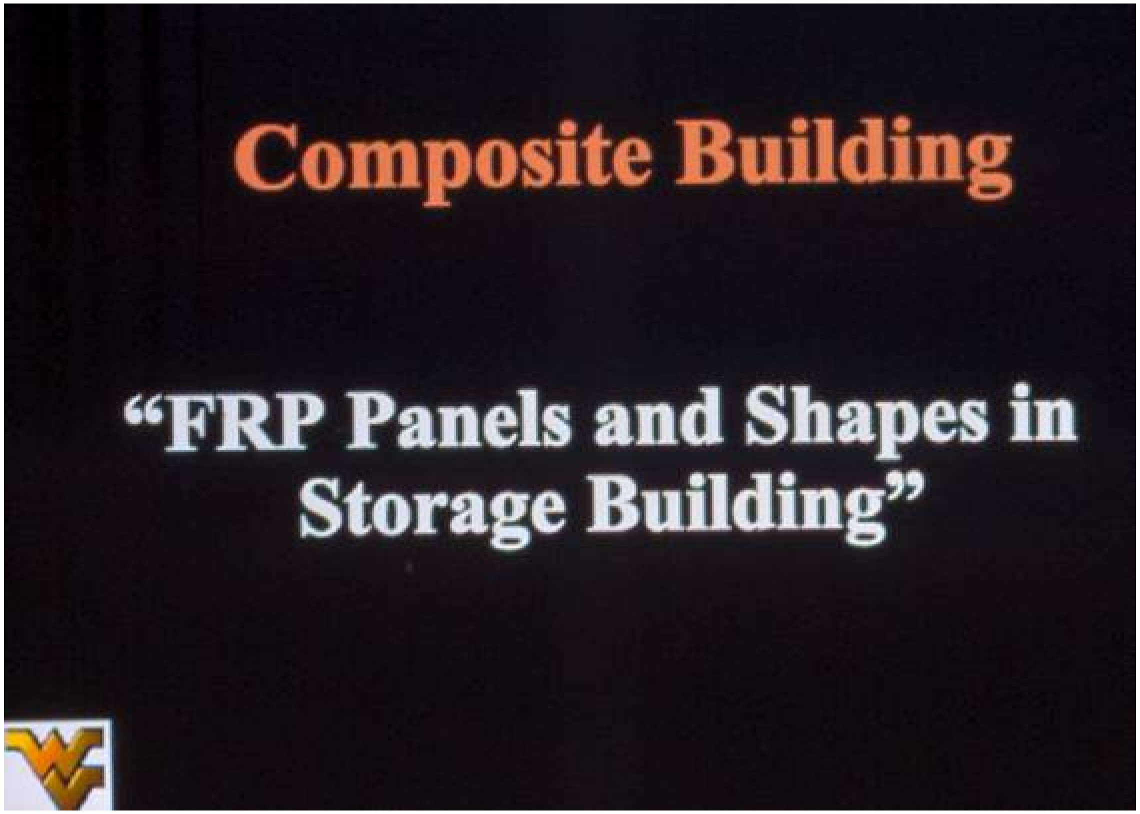
- What is an FRP? Why FRPs?
- Fiber-reinforced Plastics in Construction
- Chemistry of Synthesis
- Processing Methods
- Characterization and Properties
- All-composite Bridges
- Rebars
- Repair and Rehabilitation of Bridges
- Non-destructive evaluation techniques
- Aging Issues
- Barriers to Growth of FRPs in Infrastructure
- Questions

Fiber-Reinforced Plastics

- Continuous or discontinuous fibers in a polymer matrix
- Fiber bundles are stiff and strong, but individual fibers are fragile/brittle
- Polymers are ductile and tough, but exhibit creep
- FRPs can be strong, stiff, tough, fatigue resistant, corrosion resistant, dimensionally stable and light weight. Strength-to-weight and stiffness-to-weight ratios are large compared to metals

Logical Applications of FRPs

- Aerospace: Performance driven. Weight savings very important. Dimensional stability over wide temperature range up to 700 8F. Low volume, high cost. Labor intensive processing.
- Automotive: Low weight body panels imply improved fuel efficiency. High volume, low cost. Automated manufacturing.
- Aircraft: Recent convert to FRPs.


Composite Building
“FRP Panels and Shapes in
Storage Building”

FRPs in Construction

- Rebars for concrete bridge decks and highway pavements
- All-composite bridges
- Rehabilitation of concrete bridge components using FRP wraps
- Dowell bars in concrete pavements
- FRP grids to reinforce asphalt pavements
- Sign boards and sign posts
- Sound barriers
- Utility poles
- Guard rails
- Drainage systems – Pipes and culverts

Additional Advantages

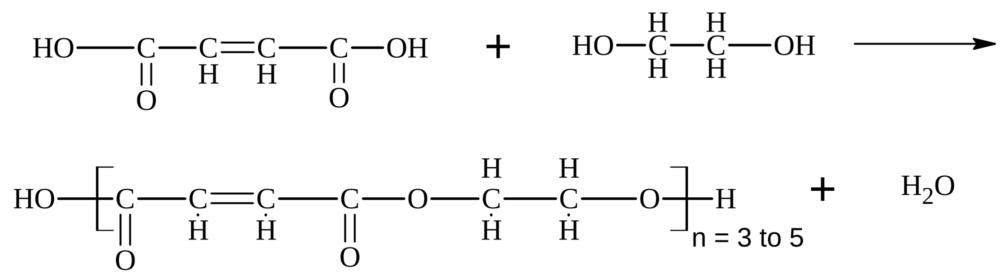
- Construction can be done off-site
- Constrution can be modular
- Transportation is easy
- Heavy machinery not needed for on-site erection
- Reduced erection time

Matrix Polymers

- Thermoplastics
- Thermosets
  - Unsaturated polyesters
  - Epoxy
  - Vinyl ester
  - Polyurethanes

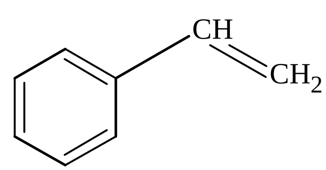
Polyester

- Condensation Reaction



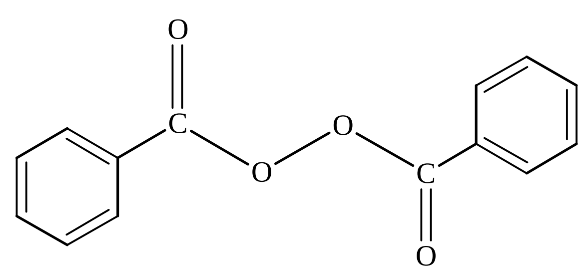
Maleic acid reacts with ethylene glycol to produce an unsaturated polyester molecule

- Solvent



Styrene molecule

- Curing initiator

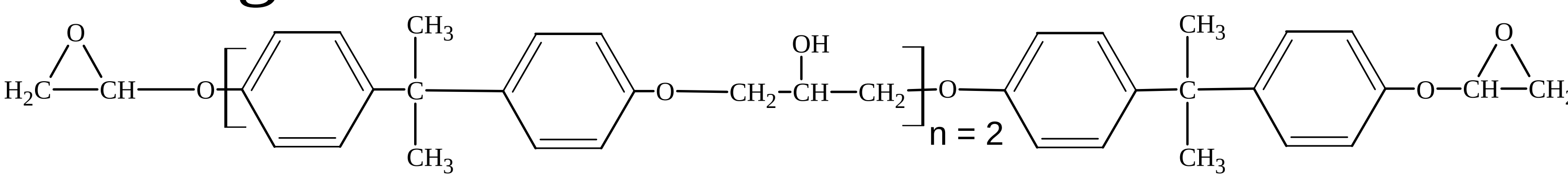


- Crosslink

Benzoyl peroxide molecule

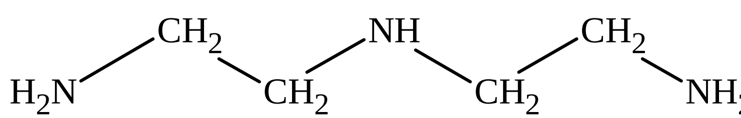
Epoxy

- Starting Material



Molecule of diglycidyl ether of bisphenol A (DGEBA)

- Curing Material

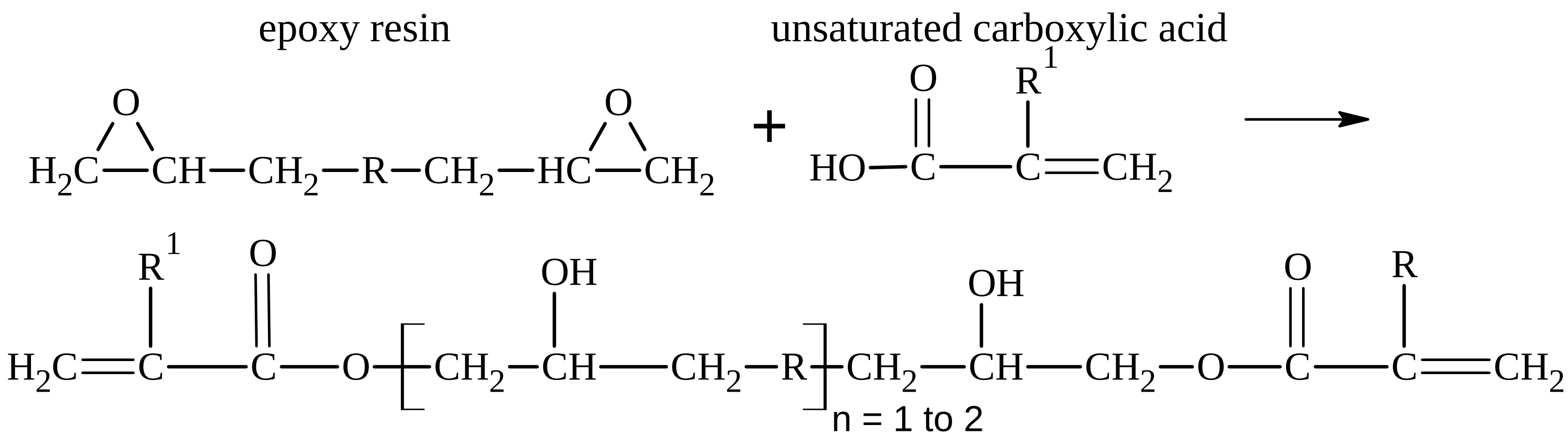


Molecule of diethylenetriamine (DETA)

- Crosslink

Vinyl Ester

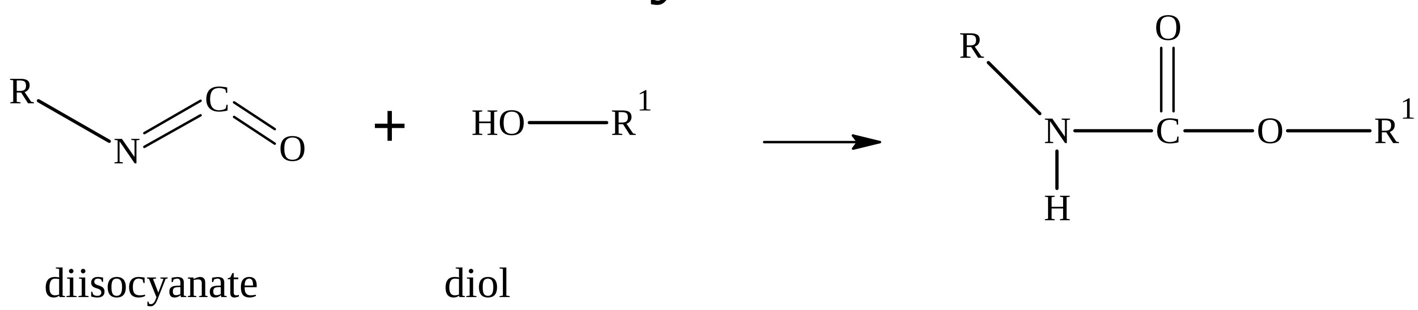
- Chemistry



- Curing and Crosslink

Polyurethane

- Basic urethane chemistry



- Crosslink with a diamine

Urethane and Vinyl Ester Blends

- Unique Features – Temp Resistance
- High Chemical Resistance
- Improved glass wettability and adhesion

According to GangaRao, Vijay and Altizer (1995), GFRP bars made with urethane modified vinylester exhibit the lowest vulnerability to different harsh environments

Fiber Reinforcement

- Glass – Least expensive. High strength and high chemical resistance. Relatively low modulus
- Carbon – High strength and high modulus
- Aramid (aromatic polyamide) – Most expensive

Fiber Forms

- Filament – Single fiber
- Strand – Several untwisted fibers
- Tow – Collection of strands (1000s of fibers)
- Roving – Tows forming parallel bundle
- Yarn – Twisted tows
- Woven Fabric – Interlacing of tows to give flat fabric
- Braid – Interlacing of tows into tubular shape

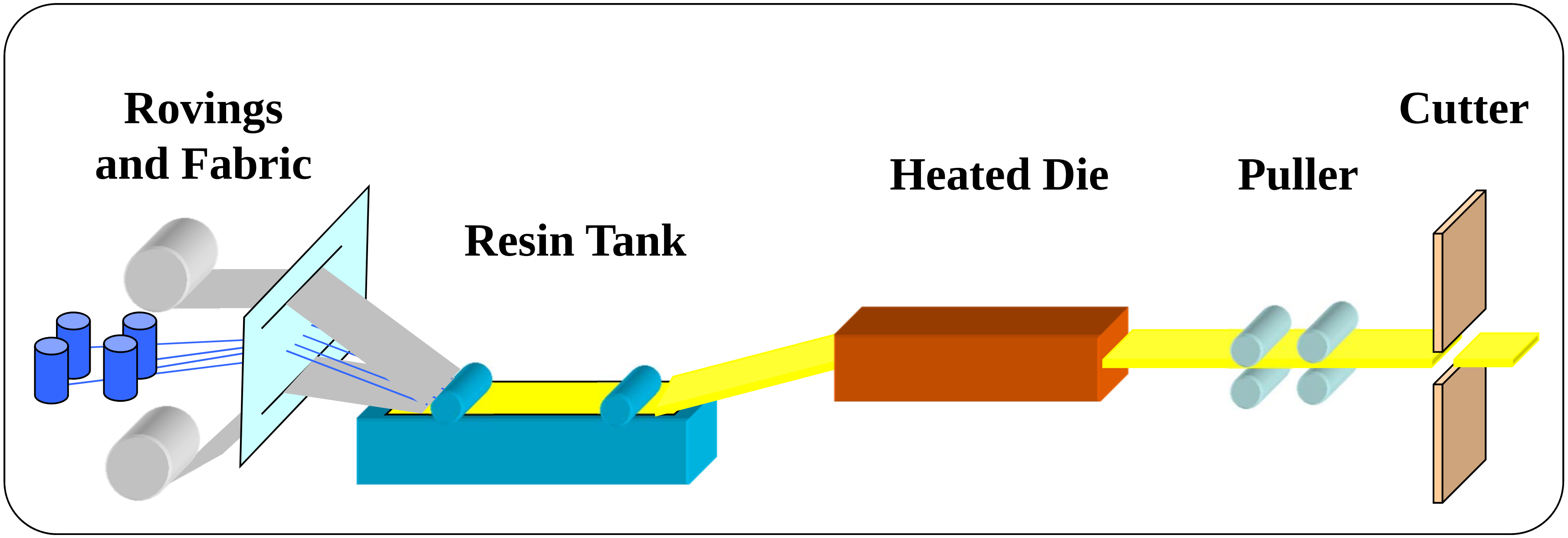
Fiber Orientation

- Fiber orientation selected by designer within limits of manufacturing process. Tapes have parallel filaments held together by a binder
- Selected orientation maximizes strength in direction where it is needed most

Manufacturing Processes

- Pultrusion
  - Resin saturated rovings are pulled through a heated die to create a constant cross section shape
- Filament winding
  - Resin saturated rovings are wound around a spinning object (mandrel) forming a cylinder

Pultrusion

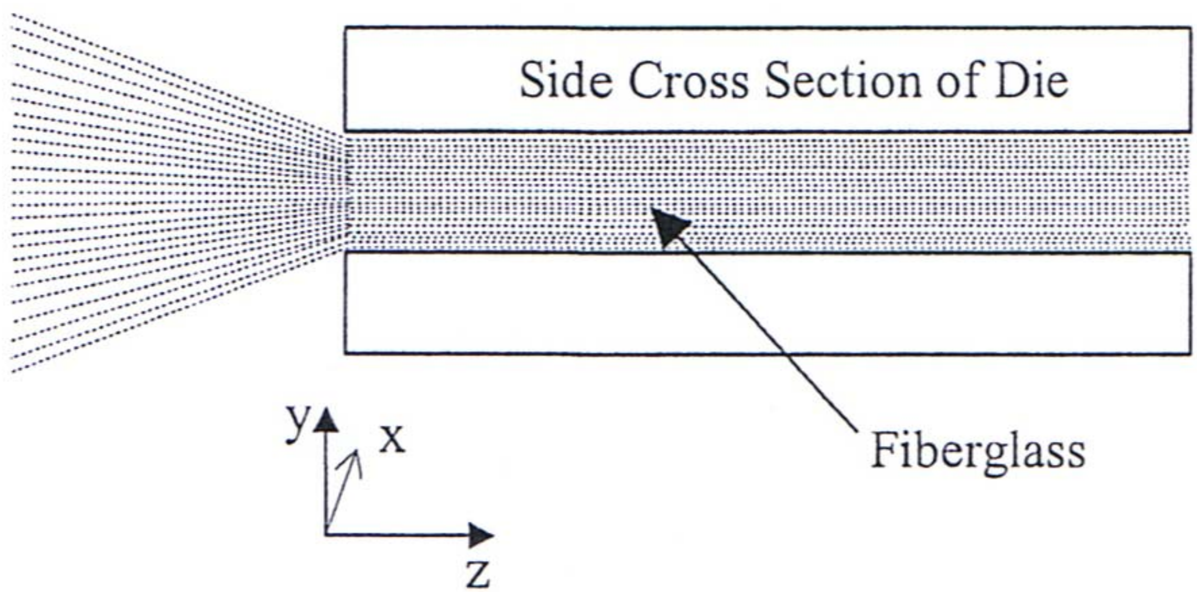


Resin contains fillers, pigments and flame retardants also

PULTRUSION

SUPERDECK™

Pultrusion Die



Pultrusion Modeling

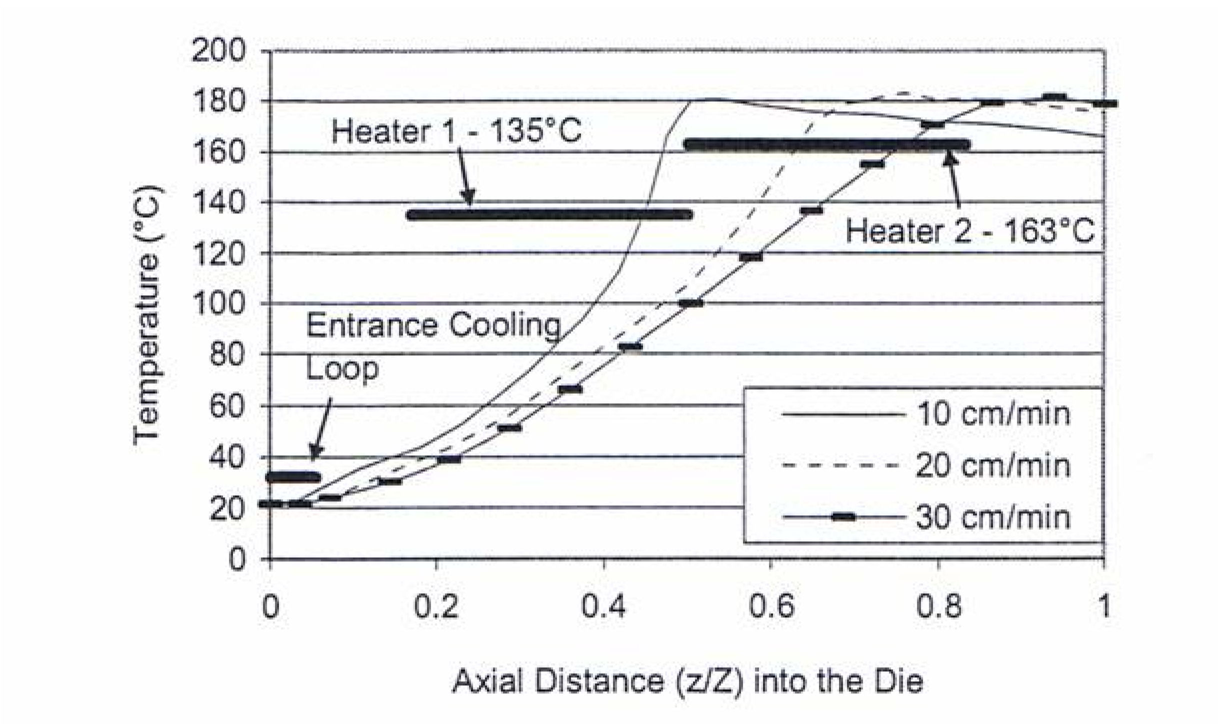
- Energy Equation $$\rho \cdot C_p \cdot \frac{DT}{Dt} = k \cdot \nabla^2 T + Q$$
- Heat Generation $$Q = \rho_r \cdot (1 - V_f) \cdot H \cdot \frac{d\alpha}{dt}$$
- Extent of Cure

$$\frac{d\alpha}{dt} = \left[A_1 \cdot \exp\left(\frac{-E_1}{RT} \right) + A_2 \cdot \exp\left(\frac{-E_2}{RT} \right) \cdot \alpha^m \right] \cdot (1 - \alpha)^n$$

- Simplified Energy Eqn.

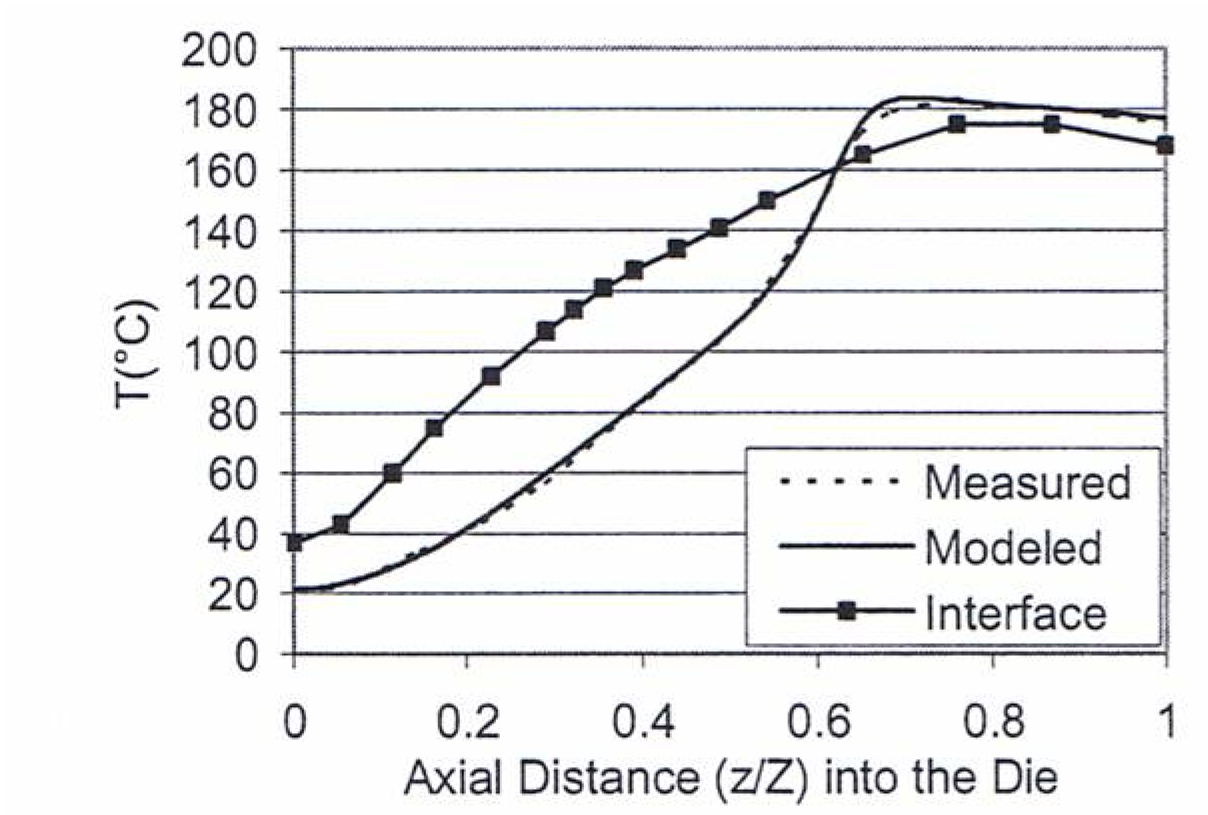
$$\rho \cdot C_p \cdot v_z \cdot \frac{dT}{dz} = k \cdot \nabla^2 T + Q$$

Die temperature profile

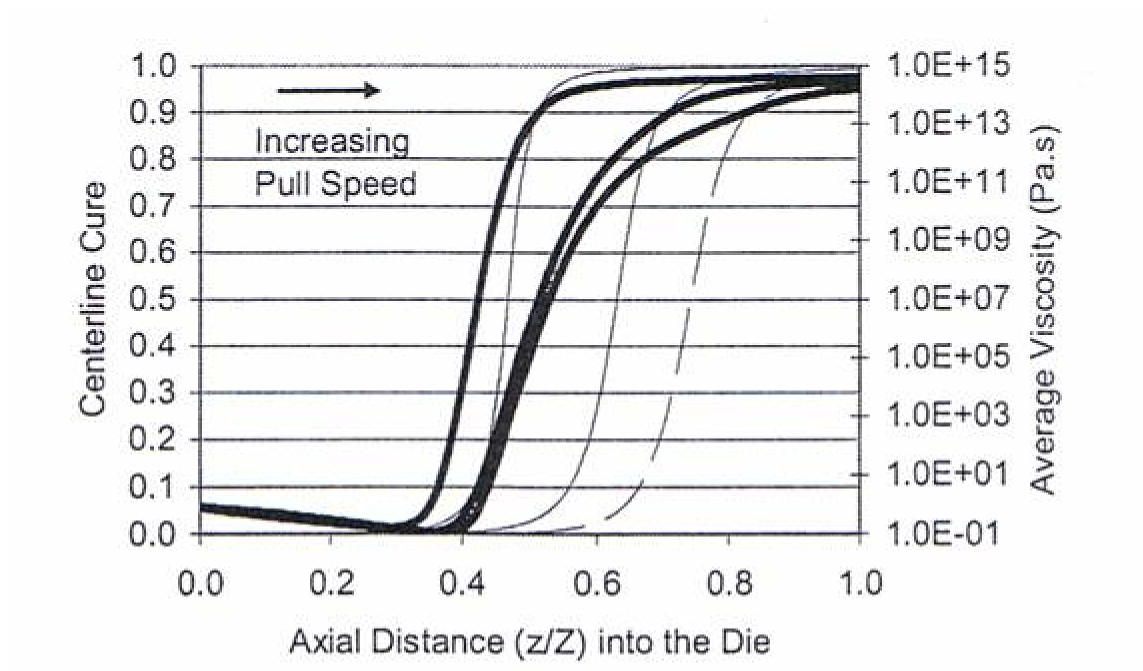


Freed, Gupta and GangaRao, SPE ANTEC, 2003

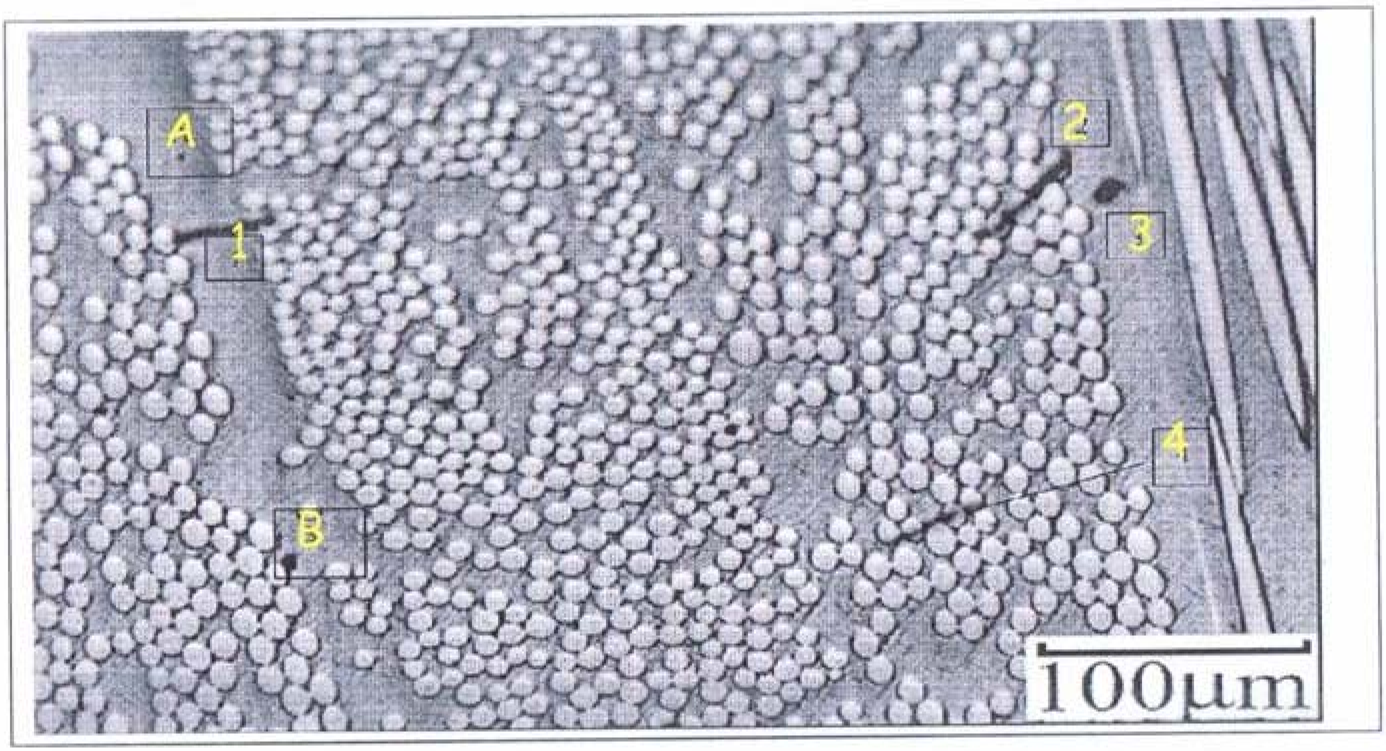
Centerline Temperature Profile



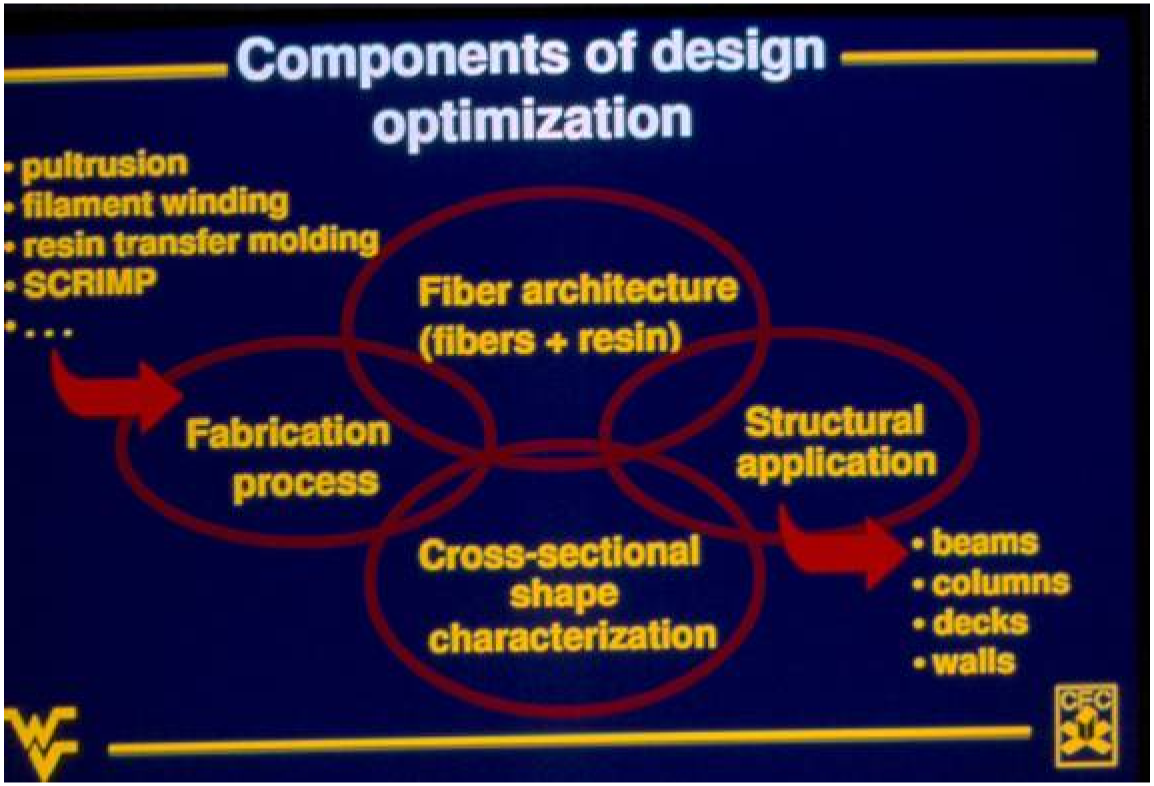
Cure and Viscosity Profiles



Structure Characterization



Mechanical properties depend on amount of voids


Components of design optimization
• pultrusion
• filament winding
• resin transfer molding
• SCRIMP
• . . .
Fiber architecture
(fibers + resin)
Fabrication process
Structural application
Cross-sectional shape characterization
• beams
• columns
• decks
• walls
CFC

Bridge Applications of FRPs

1.) Deck System Projects – Real potential is in long-span bridges

2.) Reinforcing Bar Projects

3.) Strengthening / Wrapping projects


Laurel Lick Bridge
"FRP Composite Bridge Deck on FRP Stringers with FRP Abutment Panels"

Weston, WV

Glass-reinforced vinyl ester. Built in April 1997

Piles being driven into the ground

FRP Abutment

Piles connected by FRP honeycomb

Concrete cap on top of piles

FRP Stringers

Bearing pad holds stringers to concrete cap

Urethane adhesive is applied to the stringers

FRP Bridge Deck

Each interlocking panel is 22 feet long

Completed FRP Bridge

Bridge is 22 feet by 22 feet. Wearing surface is 3/8” sand in polyester

Bridge Monitoring

Testing for deflection under live load

Live Load Test of Peel Tree Bridge

Live Load Test of Hackers Creek Bridge

Bridge Monitoring

- Static
  - Measure strains and deflections to evaluate static responses (short and long term)
- Dynamic
  - Measure acceleration, strain and deflections to evaluate the dynamic response

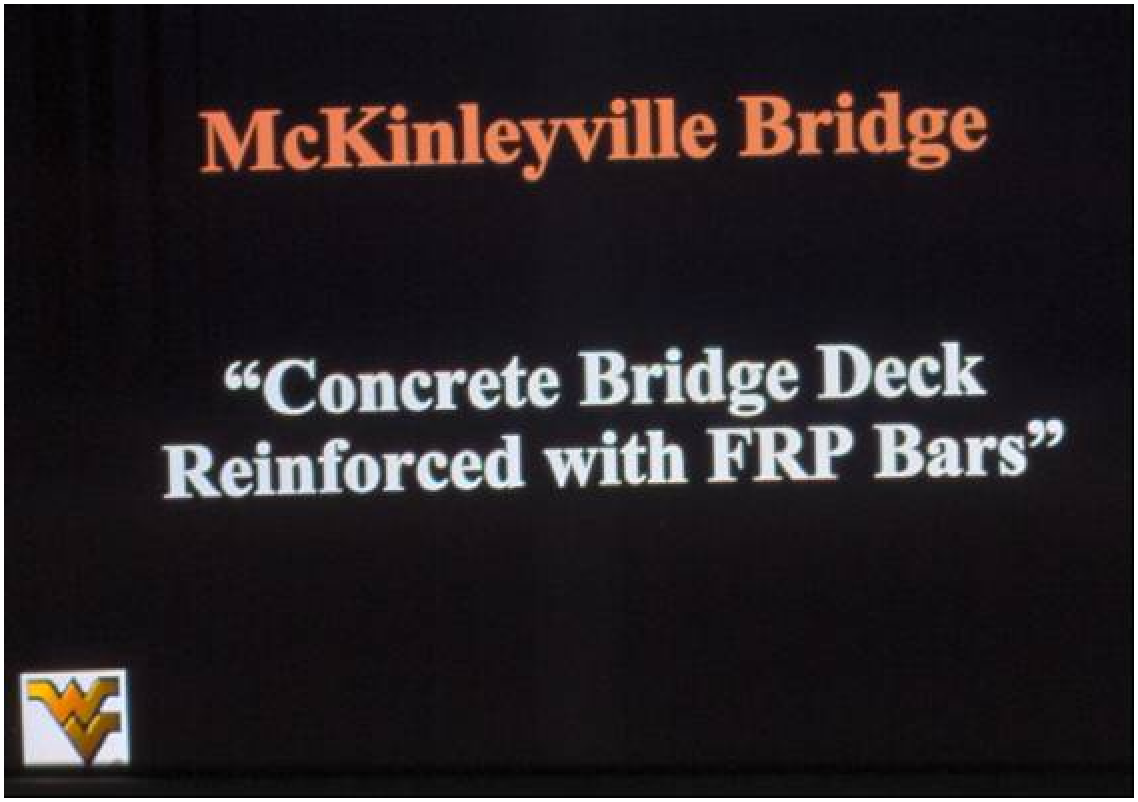
Typical Problem with Steel Reinforcement

Corrosion induced concrete deck deterioration

Taken from Aslan FRP

Solution

- FRP Reinforcing Bars
  - Not affected by chloride ions
  - There is better adhesion between FRP and concrete as compared to steel and concrete
  - Tensile strength greater than steel
  - 1/4th weight of steel
  - Design specifications and standards exist
  - Cost is competitive with steel


McKinleyville Bridge
“Concrete Bridge Deck
Reinforced with FRP Bars”


'96 10 30

Strengthening by Wrapping

Repair of Cracked Concrete Beam

Carbon fabric and epoxy used

East Street Viaduct
Parkersburg, WV

- Completed December 2000
- Glass FRP Wraps
- Wrapping done to prevent additional deterioration.

Following slides taken from presentation by Mr. Donald Williams of the WV Department of Transportation

East Street Viaduct Bridge

Inventory Report Sheet 8 of 14

Bridge No.: 54-14A-1.83 (6438)
Date: January 20, 1999

2001 UPDATE

Photo One

Abutment One North

2001 UPDATE

Photo Two

Abutment One South

East Street Viaduct Bridge

Inventory Report Sheet 11 of 14

Bridge No.: 54-14A-1.83 (6438)
ate: January 20, 1999

2001 UPDATE

Photo Seven

Underside of Top Slab

2001 UPDATE

Photo Eight

Drains Along Viaduct

East Street Viaduct Bridge

East Street Viaduct Bridge

East Street Viaduct Bridge

Seismic Retrofitting

Glass fabric and epoxy for improved ductility

Seismic Retrofitting

Successes
Katy Truss Bridge Prior

Successes
Katy Truss Bridge Post FRP

Non-Destructive Evaluation

- Periodic monitoring needed to detect subsurface defects
- Infrared thermography is a promising nondestructive technique
  - High speed data acquisition
  - Easy data interpretation
- Types of subsurface defects examined are
  - Subsurface debonds and delaminations in FRP bridge decks
  - Debonds between the FRP wrap and underlying bridge component

Basic Methodology

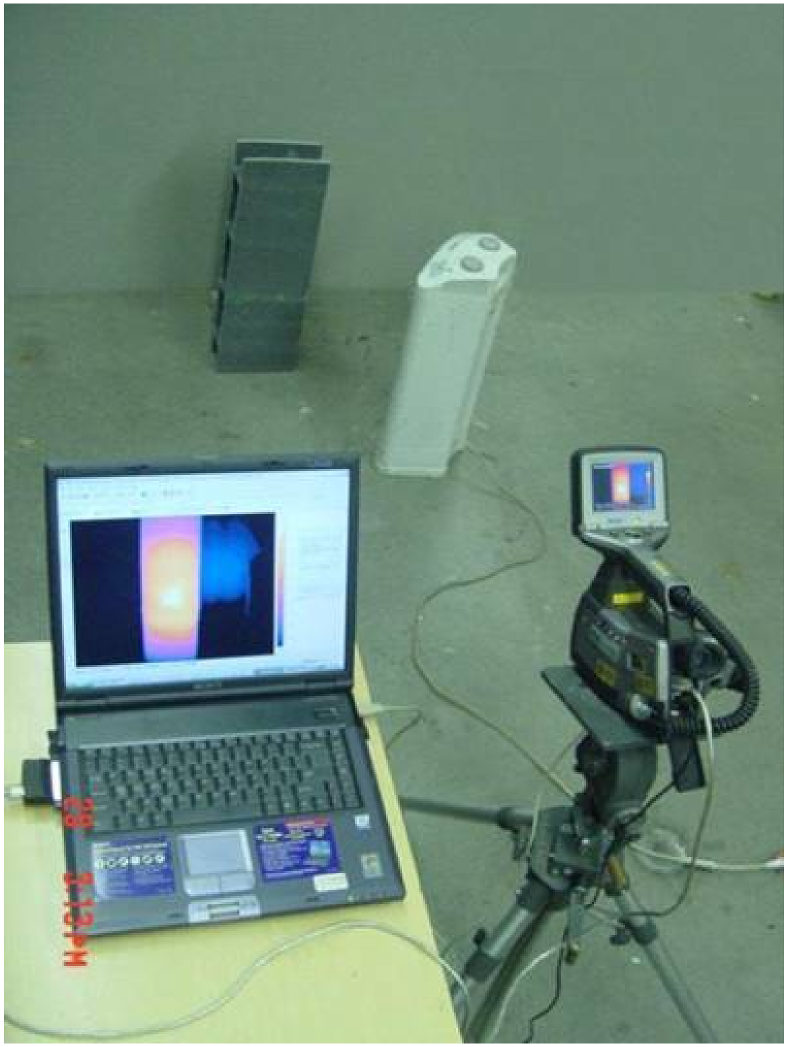
(Courtesy of Professor U. Halabe, West Virginia University)

- Infrared Thermography measures the temperature differences on the surface, by measuring the radiant emission

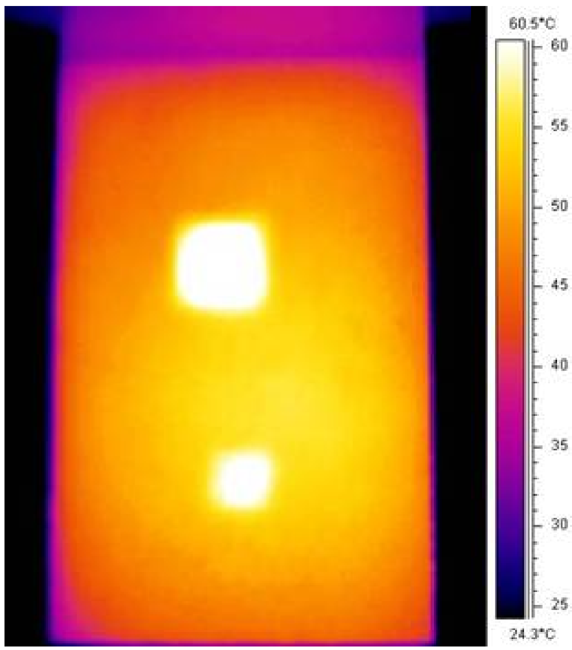
- Subsurface voids affect the rate of heat flow through a structure, thereby resulting in surface temperature differentials

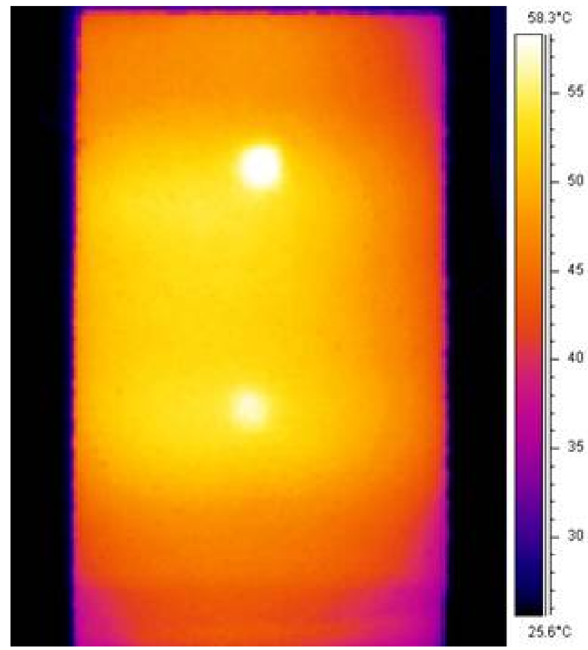
- By measuring the surface temperatures the subsurface defects can be located

Experimental Setup



…Infrared Testing – FRP Bridge Deck BD1





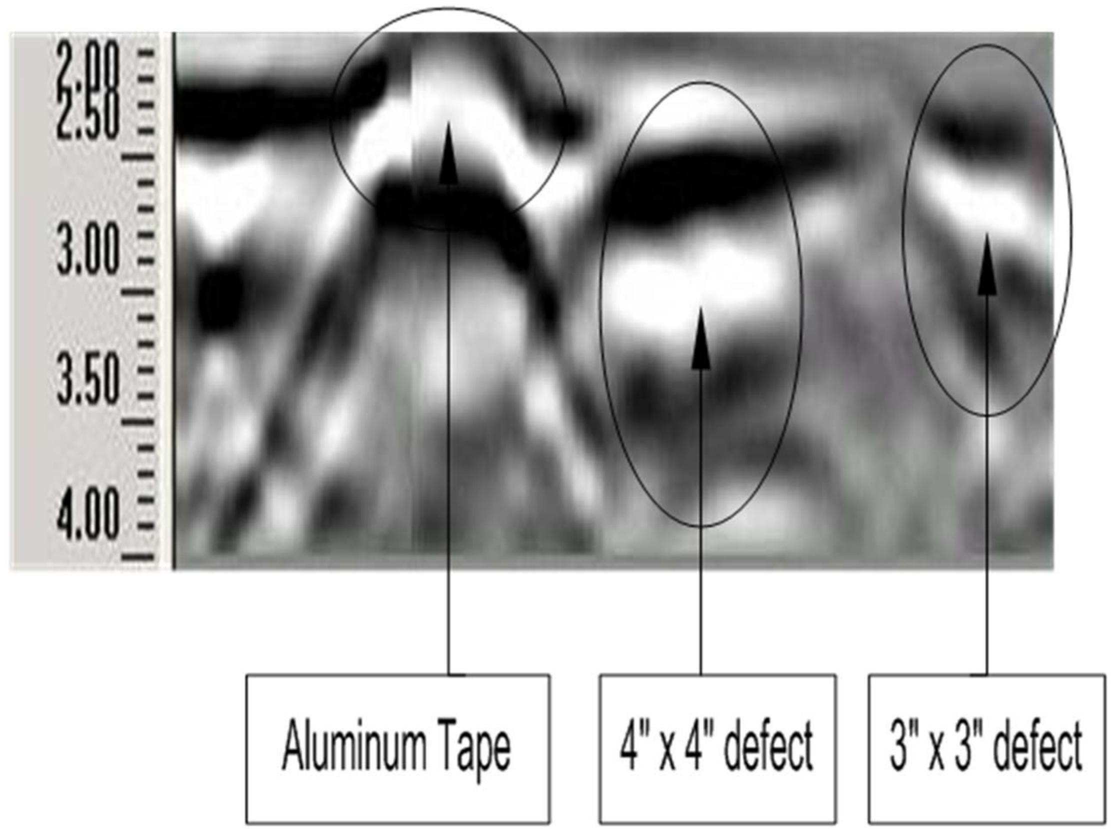
Infrared image of (a) BD1a with debonds of sizes 3” x 3” x 1/16” and 2” x 2” x 1/16”
(b) BD1b with debonds of sizes 1” x 1” x 1/16” and 1/2” x 1/2” x 1/16”

Surface Temperature difference between defect-free and debonded areas:
(a) 11º C & 8ºC (b) 8º C & 4ºC

Ground Penetrating Radar (GPR)

(Courtesy of Professor P. Klinkhachorn, West Virginia University)

- GPR is a non-contact technique that uses an antenna to transmit electromagnetic energy into a surface.
- The energy that is transmitted is reflected back by interfaces between materials with different dielectric properties, which is then collected by the antenna, converted to voltage levels, and combined to form a waveform.

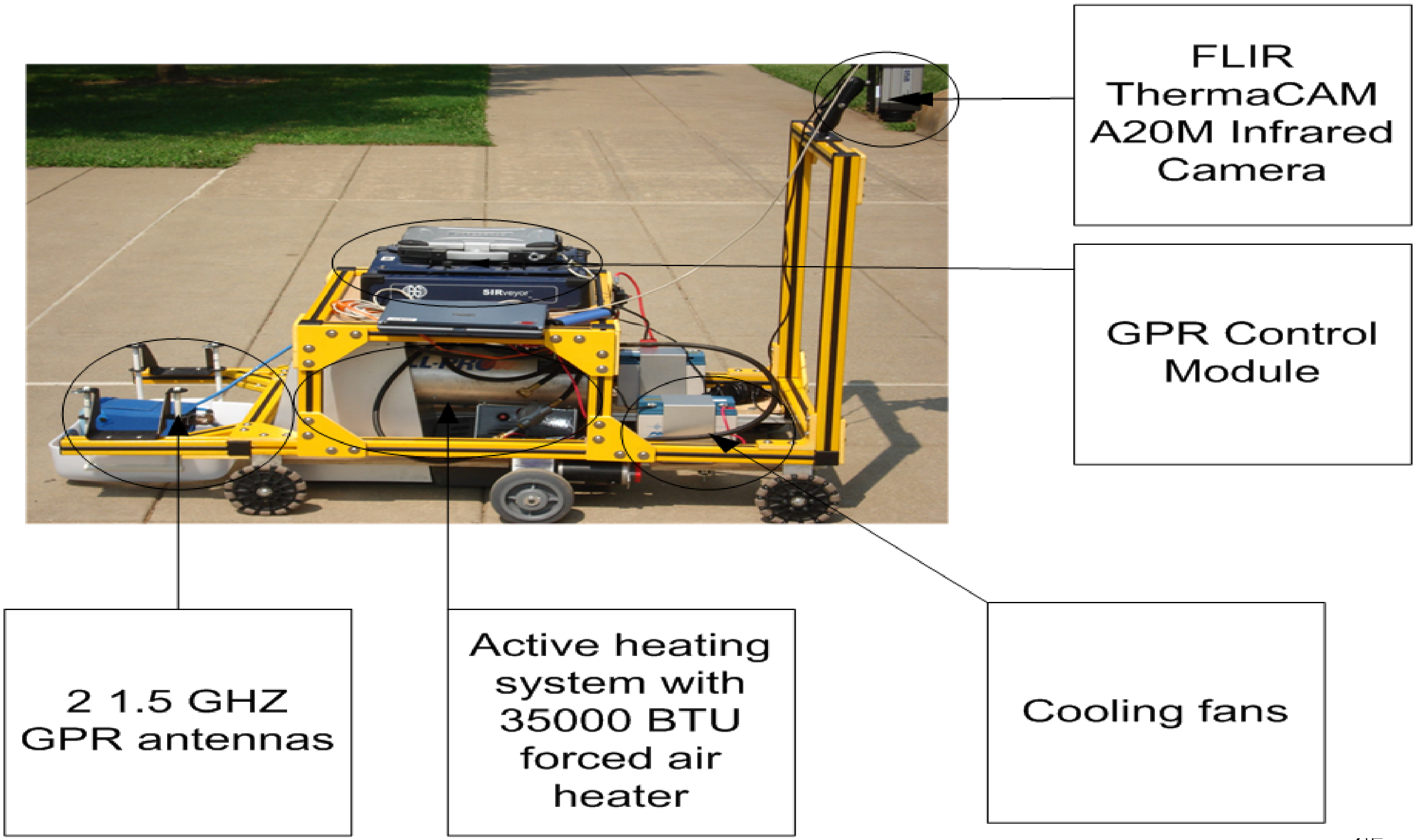


Combining IRT and GPR

- The advantages of one method can used to leverage the disadvantages of the other technology.
  - For example: GPR is sensitive to water-filled defects but has difficulty detecting air-filled defects. IRT is sensitive to air-filled defects, but has difficulty detecting water filled defects.

- Combining both methods can produce a more robust defect detection system.

Physical Implementation of UGV



Chemical Aging of FRPs

- Materials
  - Resin: Dow Derakane™ 411-350 vinyl ester resin (with 45% dissolved styrene)
  - Fiber: E-glass fiber from Vectorply Corp., 0°/90° bi-directional, 543 g/m^2
- Samples prepared by hand layup
  - 2 layers of glass fiber of 0.12 cm total thickness used
  - GFRP Sample strips cut to 10.16 cm x 2.54 cm x 0.13 cm using a tile saw

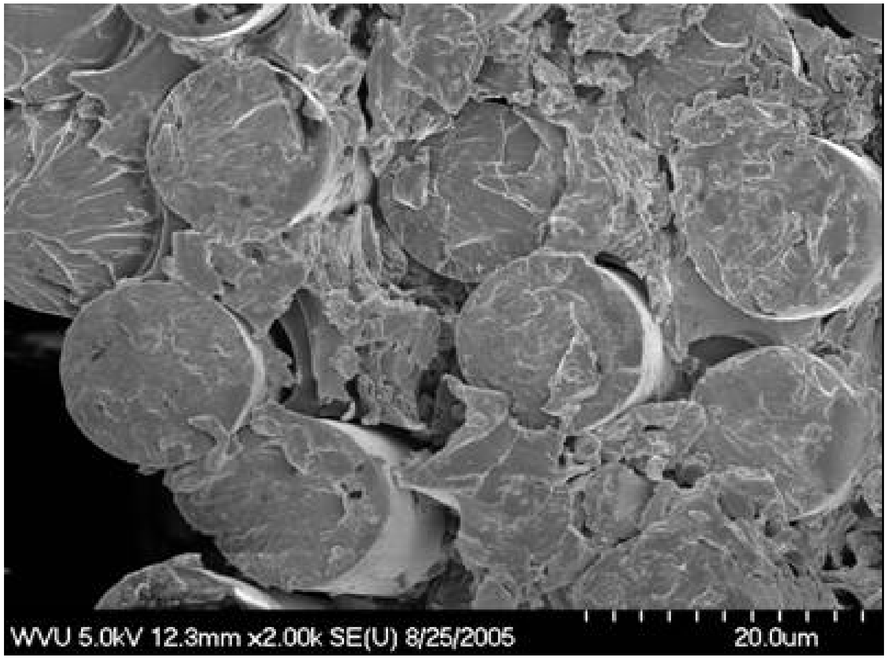
Ravindran and Gupta, SPE ANTEC, 2006

SCANNING ELECTRON MICROSCOPY

- SEM Analysis of Aged composites
  - Samples were aged in distilled water for up to 10 weeks
  - Samples were taken out every week and sectioned for SEM
  - Hitachi model S-4700 cold FE-SEM was used for analysis
  - Sectioned surfaces were sputter coated with gold to make them conductive

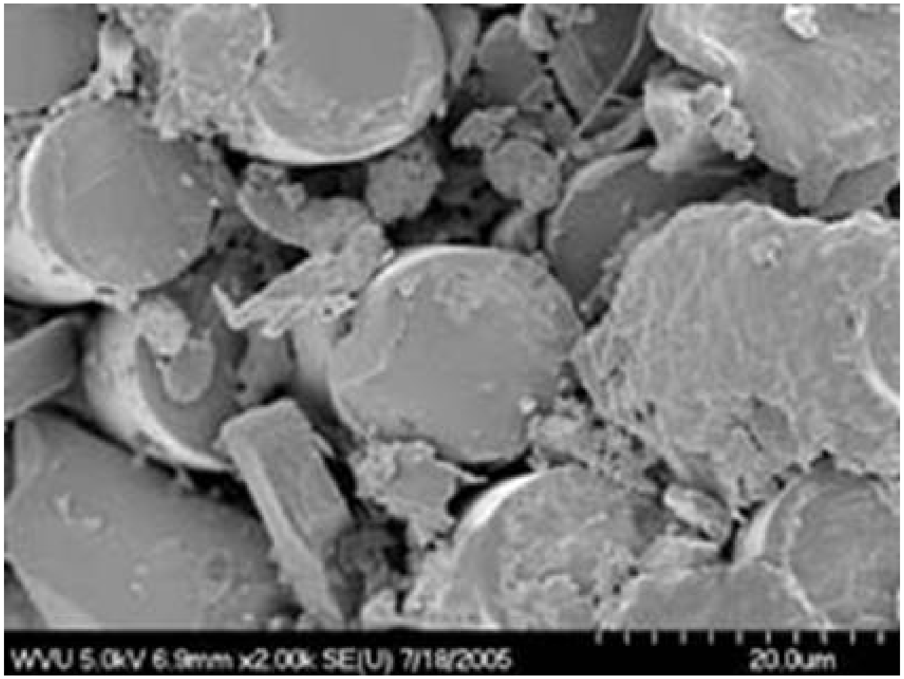
SEM Analysis - Results

- Unaged sample
- Continuous matrix
- Round fibers
- Good adhesion between fibers and matrix



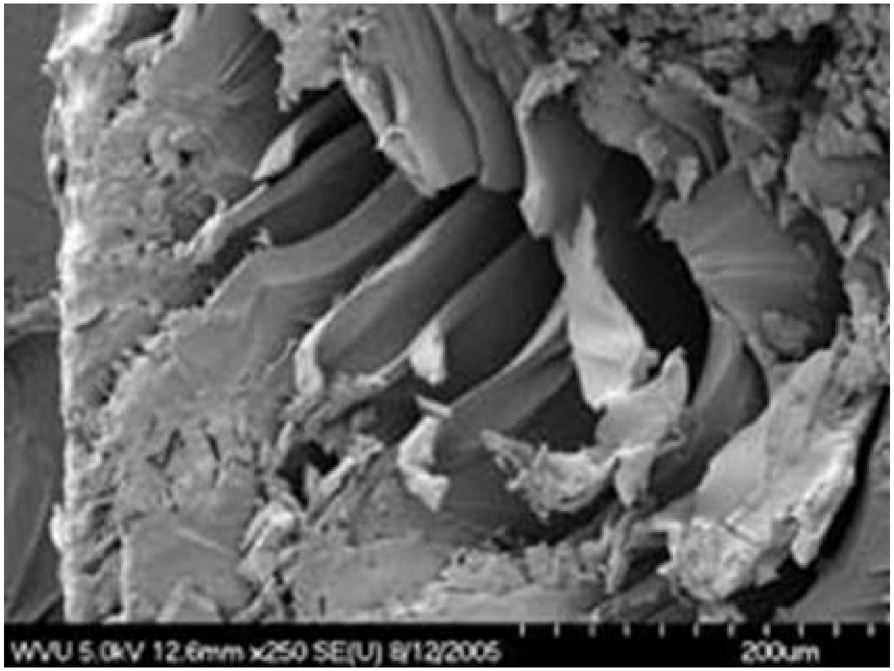
SEM Analysis – Matrix Degradation

- 4 weeks exposure and 550µm depth
- Matrix affected throughout sample



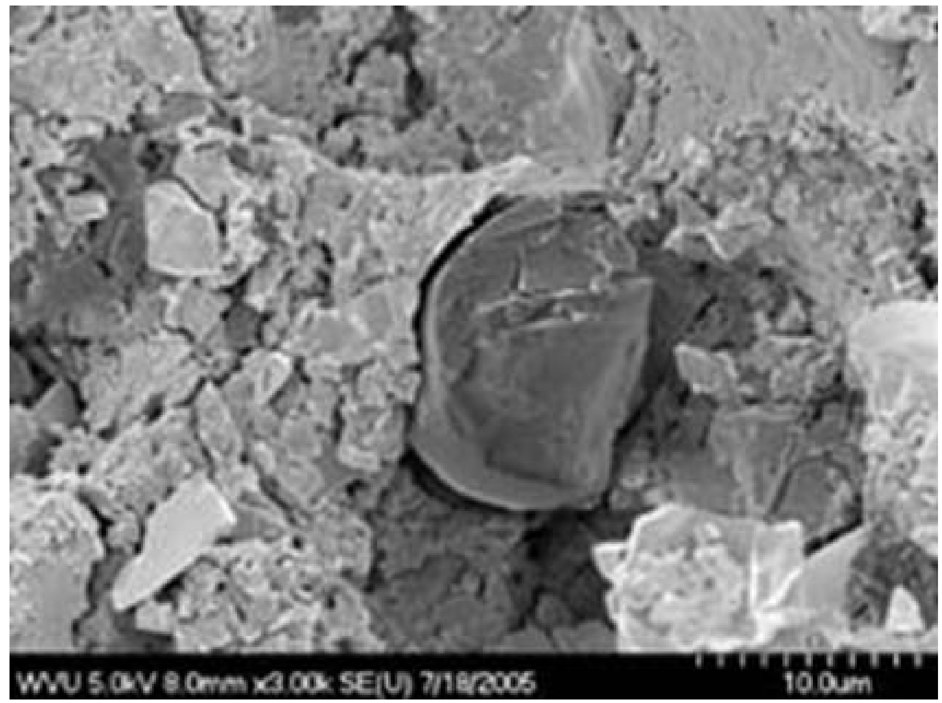
SEM Analysis – Matrix Degradation

- 9 weeks exposure and 500μm depth
- Fibers pulled out from the matrix, i.e., delamination



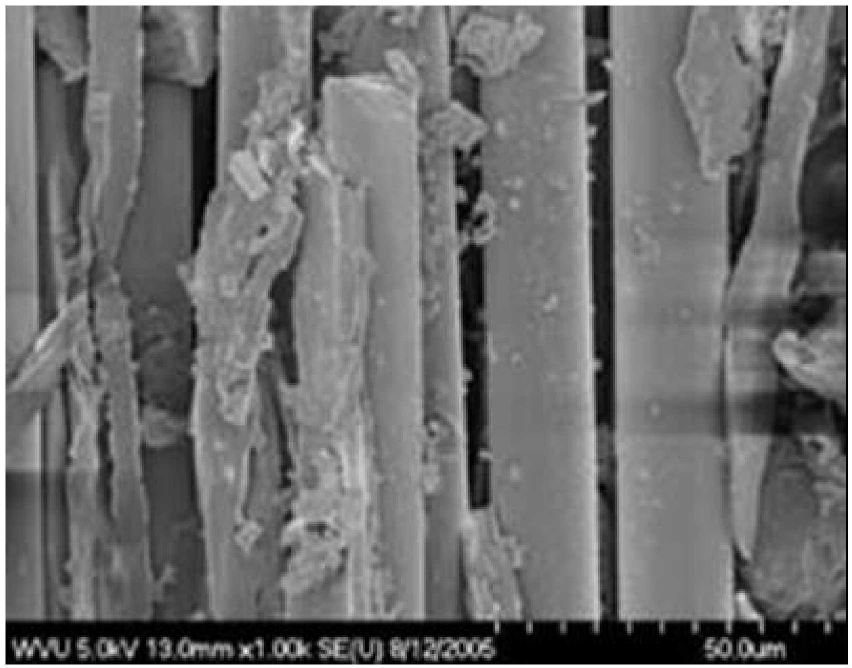
SEM Analysis – Fiber Degradation

- 4 weeks exposure and 30μm depth
- fibers are disfigured



SEM Analysis – Fiber Degradation

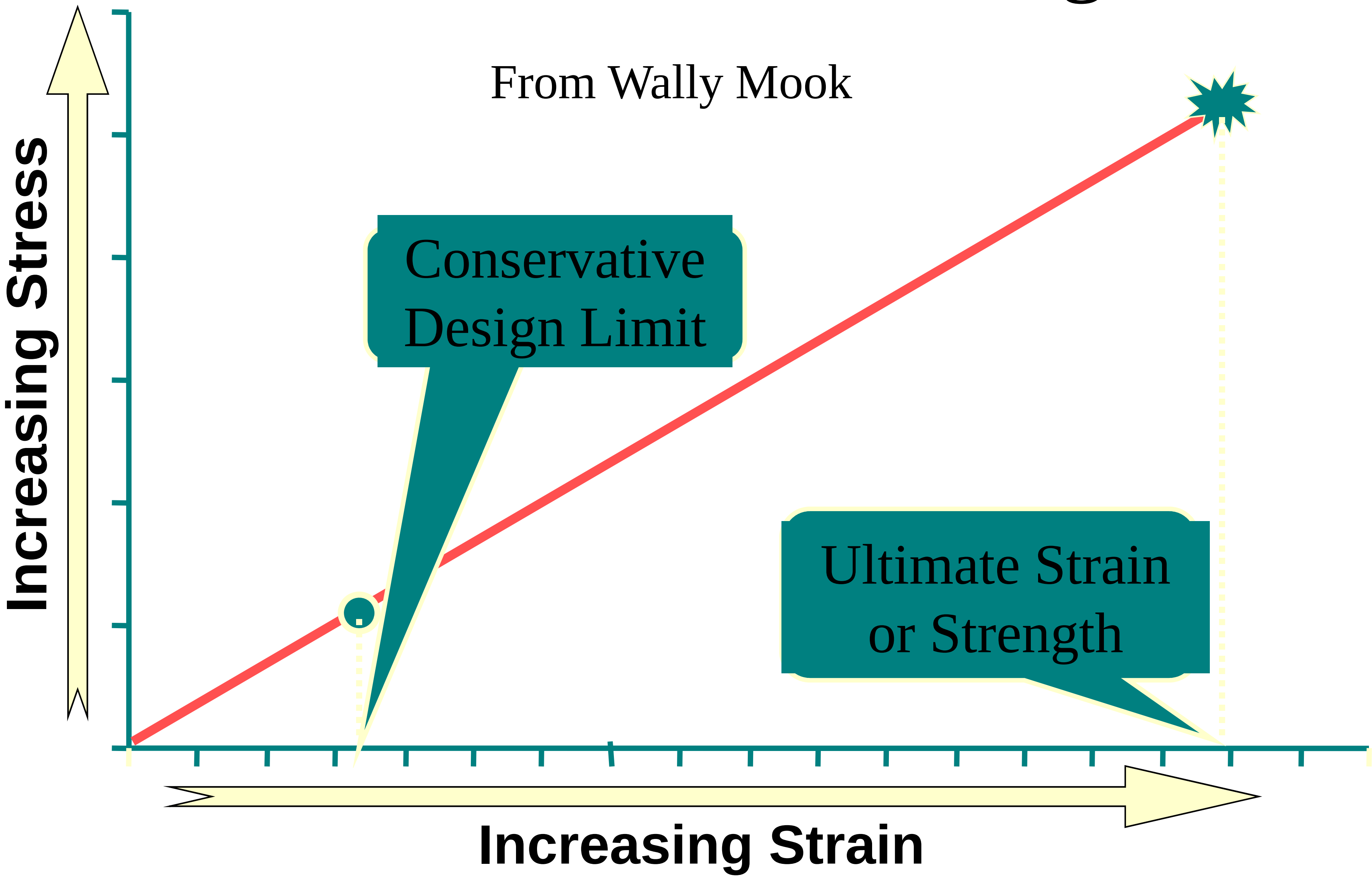
- 7 weeks exposure and 150µm depth
- Peeling off of fibers (reduction in diameter)



Barriers to Growth of FRPs in Infrastructure

Design is very conservative

Stress vs Strain – GFRP Bridge Deck



Barriers to FRP Usage

- High initial cost of FRP decks. Higher than conventional deck by a factor of 2
- Lack of adequate knowledge about FRPs. Material properties are anisotropic
- Resistance to change
- Lack of material and design specifications
- Current bidding procedures. No premium for patented technologies. Life cycle analysis not done

QUESTIONS?