CICI - Industrial Recruitment Meeting

Strength, Fatigue-life Prediction and Durability of Composites

Hota GangaRao and Ray Liang
ghota@mail.wvu.edu; rliang@mail.wvu.edu
Constructed Facilities Center, WVU

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CFC CONSTRUCTED FACILITIES CENTER

West Virginia University

STRAIN ENERGY DENSITY BASED FAILURE CRITERION FOR GFRP COMPOSITES

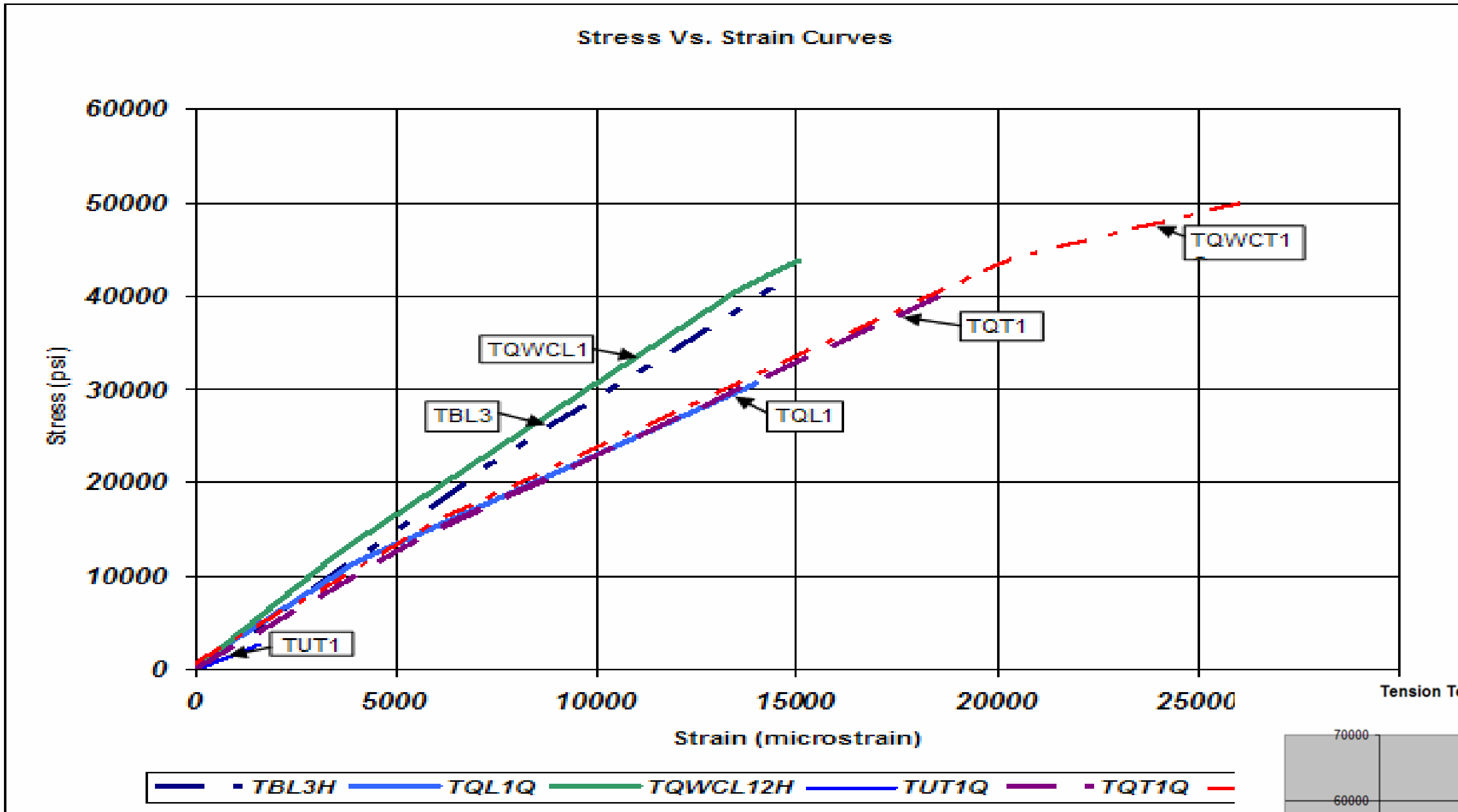
Objectives:

To predict failure strength of Glass Fiber Reinforced Polymer (GFRP) composite coupons under tension

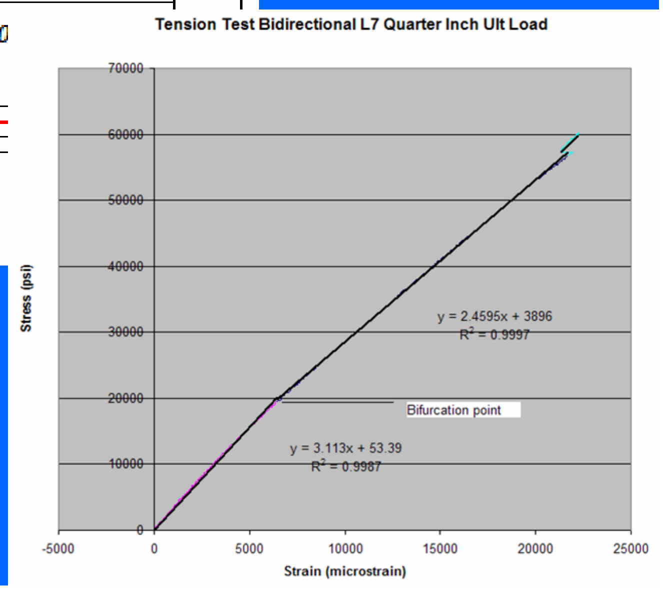
To develop a mathematical model with strain energy as damage metric predicting failure strength

To compare the predicted data with experimental data

Stress-strain Curves of Different Types of Laminates Tested in Longitudinal Direction



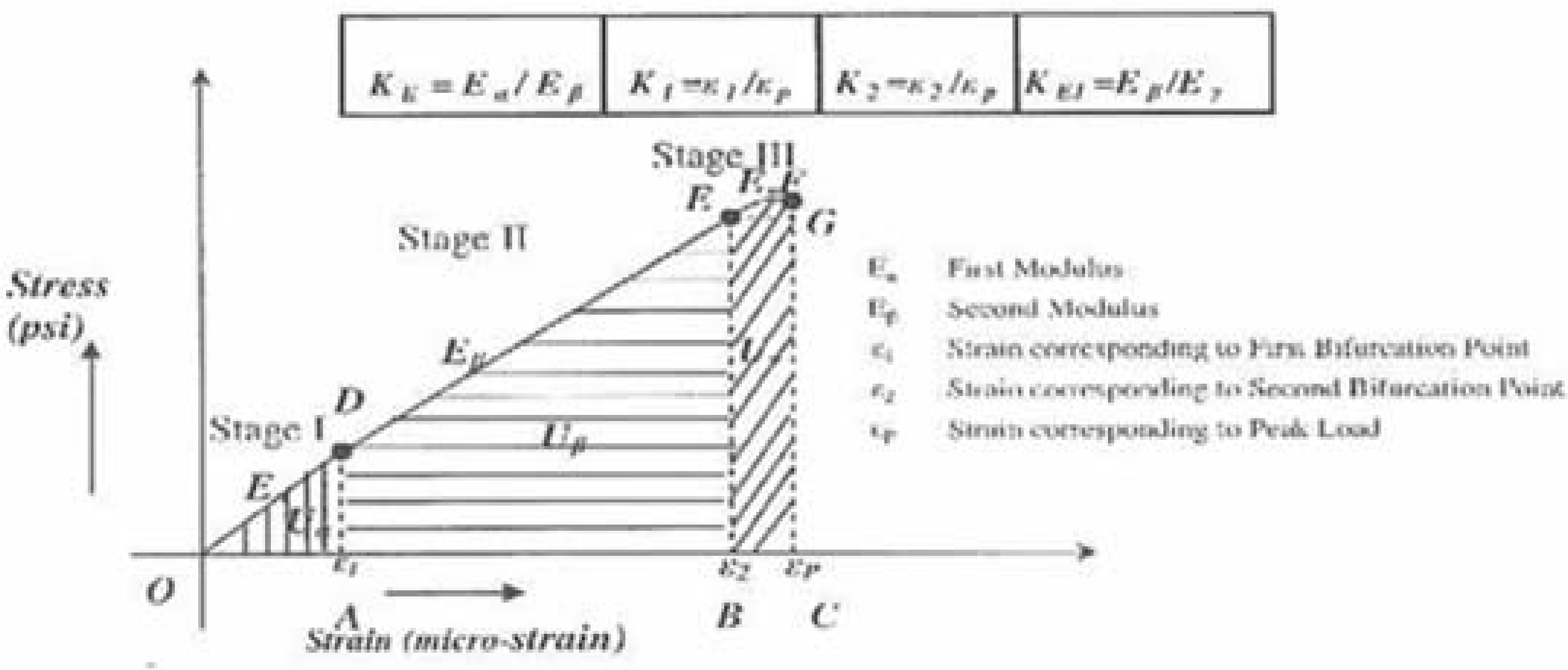
Stress-Strain of Various Types of Laminates
1 psi = 6.8947 x 10^{-3} MPa



Bifurcation Point:

The point where change in slope took place from the initial slope on a stress strain curve

Stress-Strain Curve and Strain Energy Density



Typical Stress-Strain Curve of Multi-Directional Fabric Based Composites

Strain energy per unit volume (area under the stress-strain curves) at different stages can be determined.

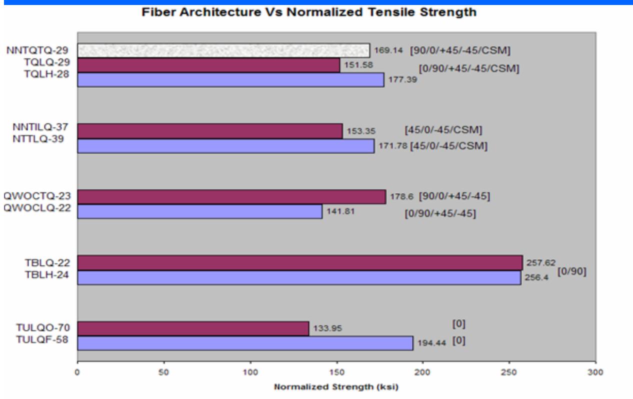
Strain Energy Based Failure Criteria

Assumptions:

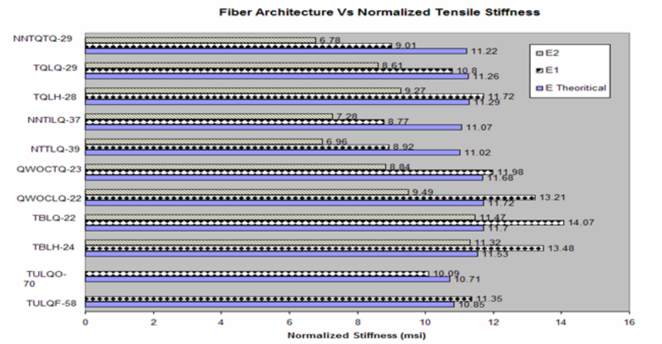
- Residual strain (i.e., strain induced during manufacture) is neglected because of small magnitudes.
- Change in initial stiffness of coupons from fiber kinking is neglected.
- Bi-axial effects are neglected
- Non-linear stress-strain response is idealized as bi-linear

  between 0 and $\varepsilon_{0.9P}$.

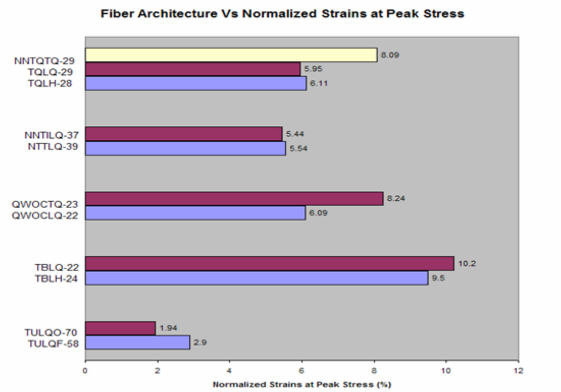
Normalized Tensile Strength, Stiffness and Strain at Peak Stress



Fiber Architecture Vs Normalized Tensile Strength
1 ksi = 6.8947 MPa



Fiber Architecture Vs Normalized Tensile Stiffness
1 msi = 6.8947 GPa



Fiber Architecture Vs Normalized Tensile Strains at Peak Stress

Comparison of Theoretical and Experimental Results

Theoretical and Experimental Comparisons of Strains at Maximum Stress

Material ID	*Fiber Architecture*	*Strain at Peak stress*	*Strain-Theo*	*%Diff*
Cross-ply	$[0/90]_{28S}$	22086.38	24102.70	8.37
Cross-ply	$[0/90]_{18S}$	22354.08	23435.63	4.61
Quadri-directional with CSM	$[0/90/+45/-45/CSM]_{10S}$	17513.67	19094.09	8.28
Quadri-directional with CSM	$[0/90/+45/-45/CSM]_{4S}$	16855.43	18284.29	7.81
Quadri-directional with CSM	$[90/0/+45/-45/CSM]_{4S}$	23445.72	25429.18	7.80
Quadri-directional	$[0/90/+45/-45]_{4S}$	13321.04	13733.78	3.01
Quadri-directional	$[90/0/+45/-45]_{4S}$	18550.51	20332.99	8.77

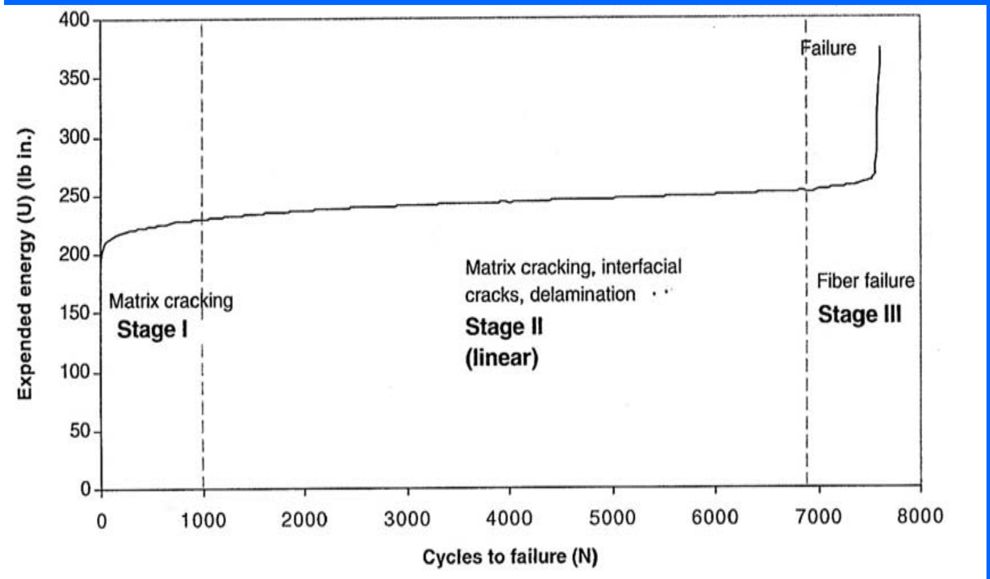
Conclusions

Damage mechanism is hypothesized to be a progression from matrix softening, matrix micro-cracking, and interaction of micro cracks leading to delamination and fiber breakage.

The experimental and predicted strains and stresses were within 10% for all different fiber architectures and their volume content.

FAILURE STRENGTH THEORY USING INTERNAL STRAIN ENERGY APPROACH

Stages of Strain Energy Loss under Fatigue Loading



Typical strain energy vs. fatigue cycles (energy curve) of a GFRP composite under tension-tension fatigue (Natarajan et al, 2005)

The increase in expended strain energy in FRP composites under cyclic loading with the number of fatigue cycles is defined by 3 distinct stages:

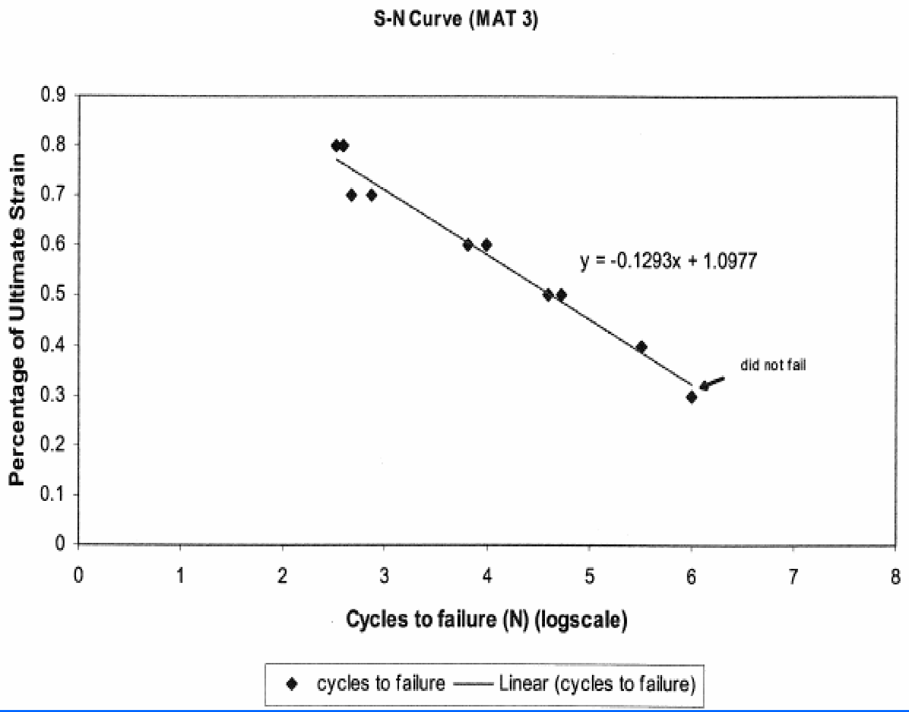
Stage I: initial loss of energy due to matrix microcracking, ~ 10-15% of fatigue life

Stage II: steady energy loss linearly varying with number of cycles, reflecting crack propagation and delamination across the thickness, ~ 70-75%

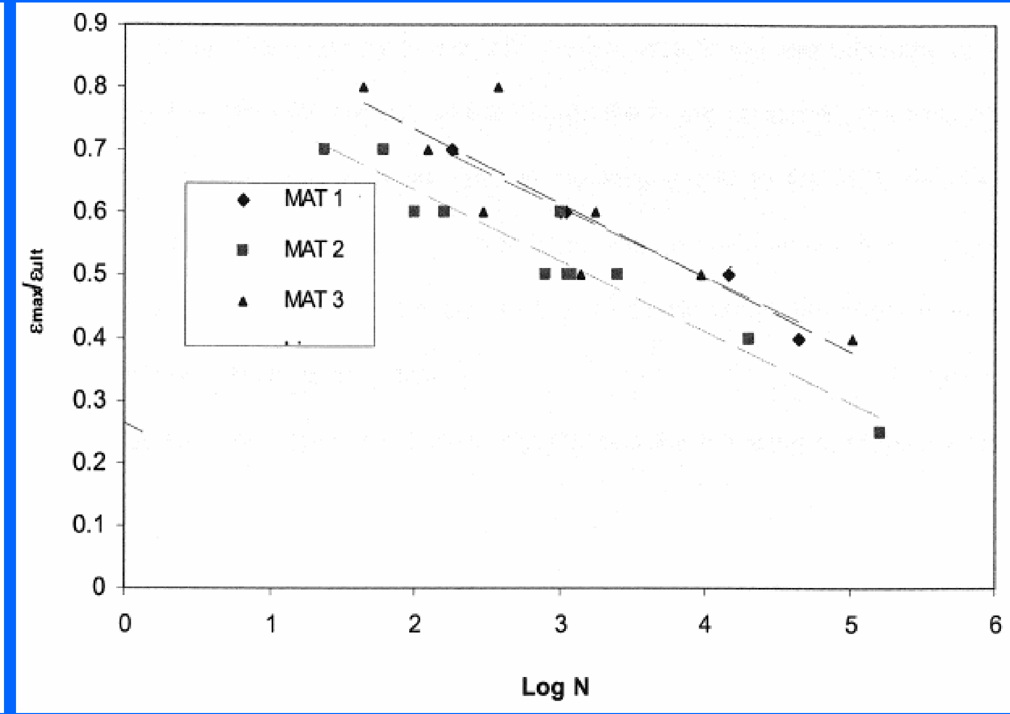
Stage III: abrupt energy loss leading to fiber breakage and specimen failure, ~ 10%

The energy loss rate in Stage II is the characteristic of a material for a given load or strain range and is used to predict the useful life of the material.

Typical Ultimate Strain versus Fatigue Cycles Plot



Variation of Number Cycles to Reach Stage II with Normalized Max Applied Strain



Fatigue Life Prediction Model Using Energy Curve:

$$N_f = \frac{U_f - U_0}{a\left(\frac{\varepsilon_{max}}{\varepsilon_{ult}}\right)^b}$$

Uf : The strain energy of the material at failure

U0 : The internal strain energy of the material before fatigue loading

DURABILITY OF POLYMER COMPOSITES UNDER THERMO-MECHANICAL LOADS AND AGING TEST METHODOLOGY (ATM)

Objectives:

To use the aging testing methodology (ATM) to evaluate/predict long-term performance of FRP composites in terms of life prediction models and/or master curves

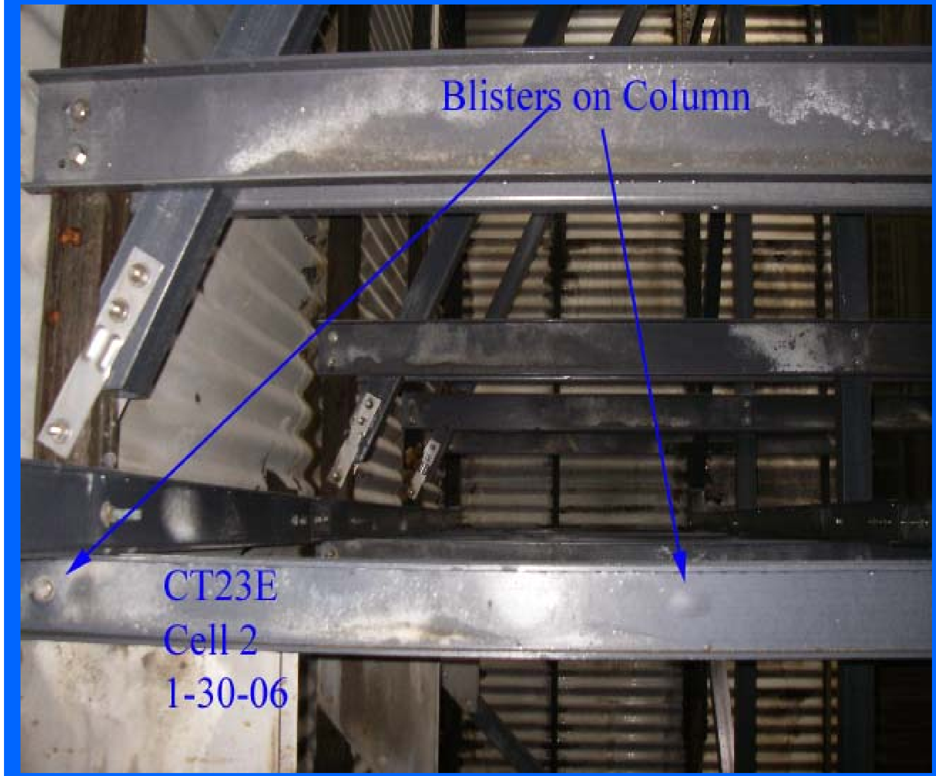
To design and develop more durable structures in terms of safety (knock-down) factors based on data collected by ATM

Chemical and/or Physical Degradation

Examples of Corroded Pultruded FRP Members

(Mosallam, 2001)

Blisters of Pultruded FRP Members



UV Degradation of FRP Wrap

A Strategy of Accelerated Testing Methodology (ATM)

The long-term response/performance of composite structures exposed under the actual environments of load, temperature, water, and others must be established.

Conditioning Methods and Parameters

- Immersion bath (Sorption)
- Sustained loading
- Freeze-thaw
- Fatigue
- Combination of the above

- pH (salt solutions pH3, 7 &13, water, sea water) and dry
- Humidity
- Temperature (-20F - RT - 150F)
- Stress/strain (25- 40- 60%)
- Freeze-thaw as per ASTM or Specs

Over a period of months and years

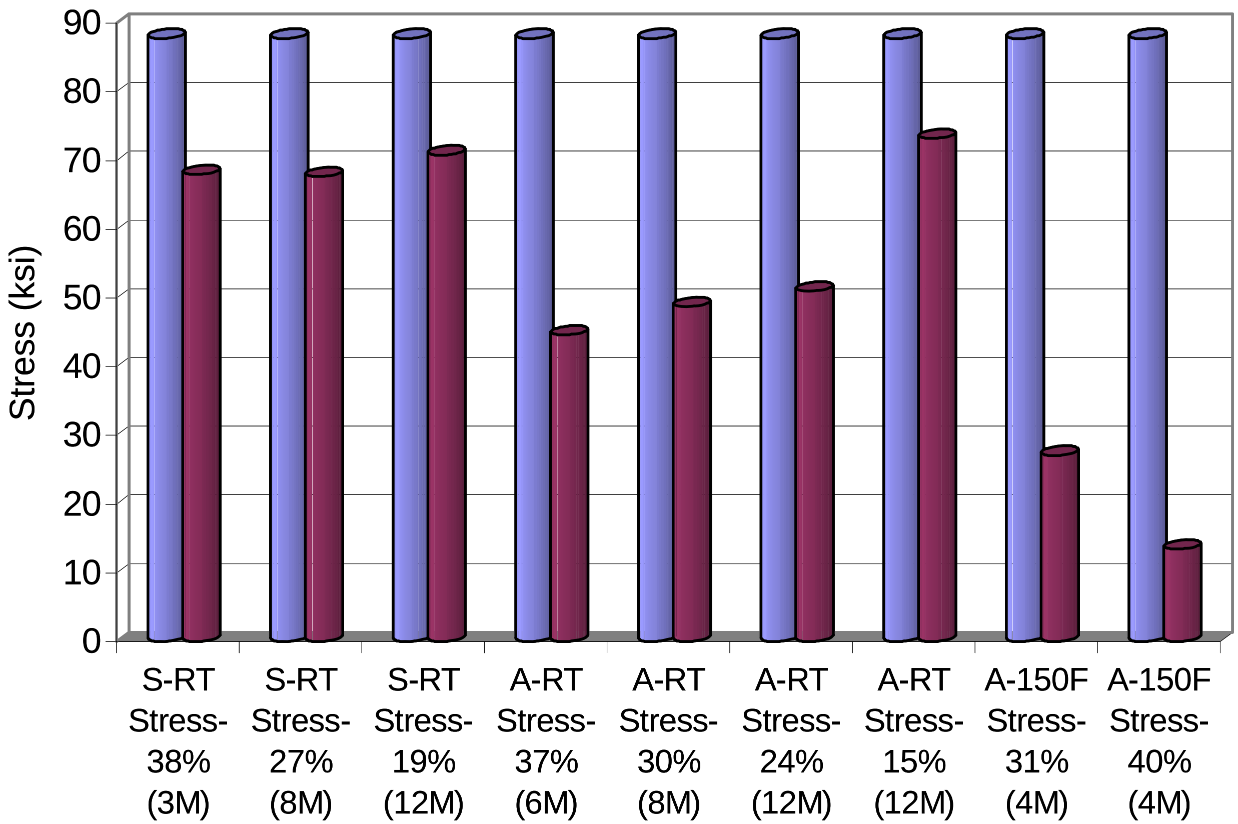
- Lab accelerated aging
- Field (natural) weathering

Test Methods

- **Tension/compression**
  - **Static**
  - **Fatigue**
- **Bending**
  - **Static**
  - **Fatigue**
- **Creep**
- **Stress Relaxation**

CFC: Capable of testing from coupons to system levels

Tensile Stress Degradation of Sand-coated GFRP Rebars under Different Conditioning



S:Salt A:Alkaline RT:Room Temp. 150F:150^{0}F Temperature M:Months

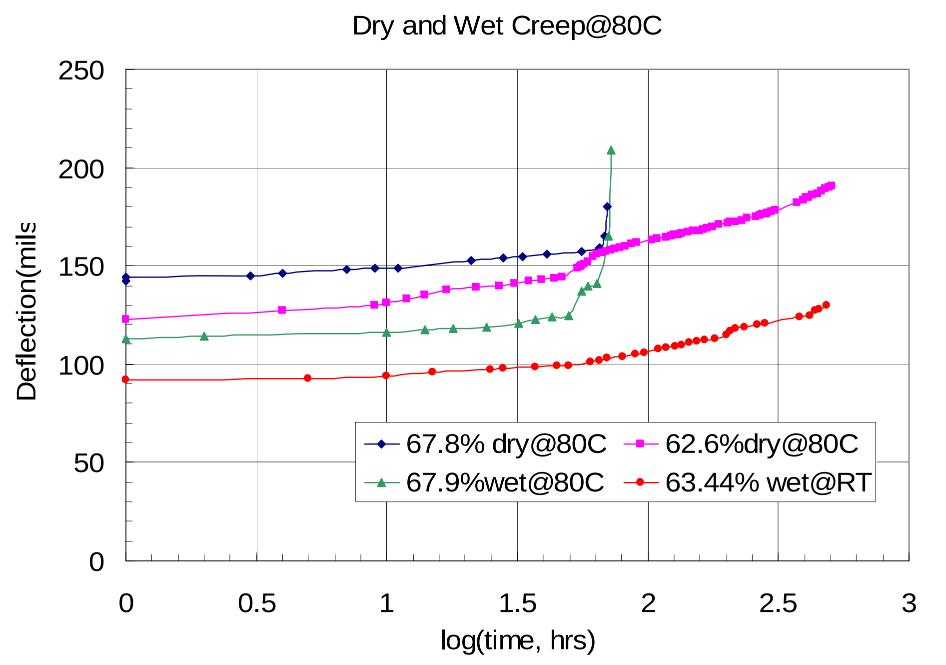
Vijay and GangaRao, 1999

Alkaline Sustained-load Test of E-glass/Vinyl Ester Composites with Nanoclay (CFC Data)

% Clay	Original tensile strength (MPa)	Residual tensile strength (MPa) and percent change w/o sustained load	Residual tensile strength (MPa) and percent change w sustained load -18.75%
0	205.77 (15.41)	206.48 (9.62) + 0.35%	189.6 (19.24) - 7.51%
1	207.30 (13.71)	211.23 (16.54) + 1.90%	182.24 (17.82) - 12.39%
2	215.04 (15.76)	216.91 (12.19) + 0.87%	176.23 (17.89) - 18.03%

Comparison in tensile strength between un-aged GFRP, and GFRP aged with and without sustained load in alkaline solution for 6 months

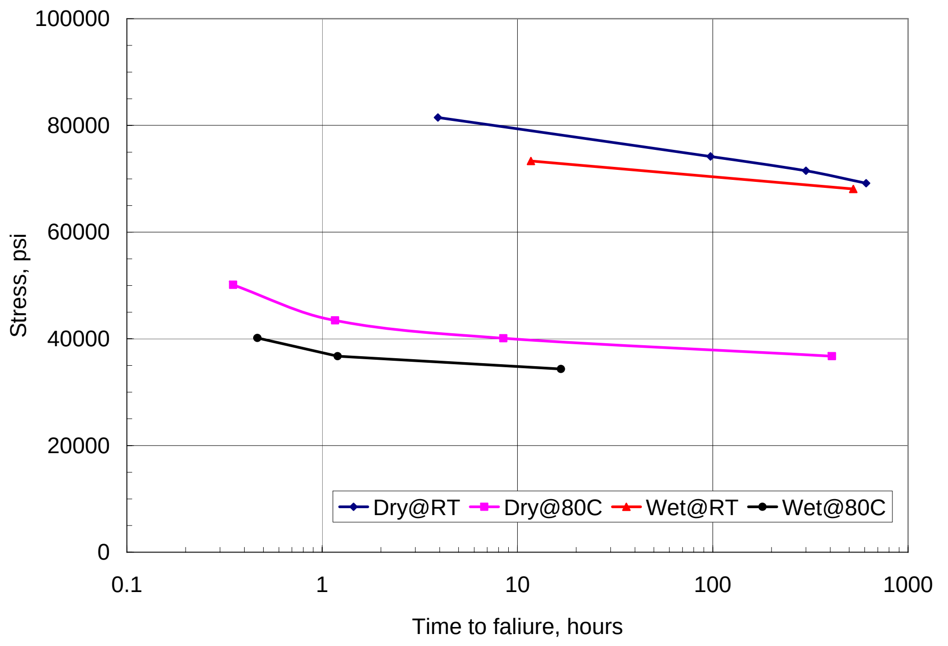
Creep Rupture Test of Pultruded Unidirectional Laminates (US Army Corps of Eng/Kazak)



Creep rupture tests at higher percent of rupture loads are used to determine the time necessary to produce failure. Data in terms of deformation/strain versus time can be used to extrapolate time to failure under lower loads for general design use.

Objective:

To generate experimental creep rupture data for better understanding of creep response phenomena including creep rate, and to establish safe applied sustained load as a percent of ultimate strength of FRP composites



Conclusions

- Both the strength prediction and fatigue life prediction models have been studied with internal strain energy as damage metric. The predicted thermo-mechanical responses at various strain levels are found in good agreement with experimental values. The internal energy approach appears to have a great potential for further development.

- Inadequate understanding of the durability behavior has the potential for either under designing or under using structural systems with FRP composites. Life prediction model(s) for the durability of composites over a range of chemo-thermo-mechanical environments has to be developed from accelerated test data and validated from field studies.

- Yr 1 deliverables: will provide: 1) strength and fatigue life prediction equations for GFRP coupons; 2) safety (knock-down) factors for GFRP coupons for applications as specified by Industry.