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

October 22, 2008
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

**Bifurcation Point:**
The point where change in slope took place from the initial slope on a stress strain curve
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
Comparison of Theoretical and Experimental Results

Theoretical and Experimental Comparisons of Strains at Maximum Stress

<table>
<thead>
<tr>
<th>Material ID</th>
<th>Fiber Architecture</th>
<th>Strain at Peak stress</th>
<th>Strain Theo</th>
<th>%Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-ply</td>
<td>[0/90]$_{3S}$</td>
<td>22086.38</td>
<td>24102.70</td>
<td>8.37</td>
</tr>
<tr>
<td>Cross-ply</td>
<td>[0/90]$_{18S}$</td>
<td>22354.08</td>
<td>23435.63</td>
<td>4.61</td>
</tr>
<tr>
<td>Quadri-directional with CSM</td>
<td>[0/90/+45/-45/CSM]$_{10S}$</td>
<td>17513.67</td>
<td>19094.09</td>
<td>8.28</td>
</tr>
<tr>
<td>Quadri-directional with CSM</td>
<td>[0/90/+45/-45/CSM]$_{4S}$</td>
<td>16855.43</td>
<td>18284.29</td>
<td>7.81</td>
</tr>
<tr>
<td>Quadri-directional with CSM</td>
<td>[90/0/+45/-45/CSM]$_{4S}$</td>
<td>23445.72</td>
<td>25429.18</td>
<td>7.80</td>
</tr>
<tr>
<td>Quadri-directional</td>
<td>[0/90/+45/-45]$_{4S}$</td>
<td>13321.04</td>
<td>13733.78</td>
<td>3.01</td>
</tr>
<tr>
<td>Quadri-directional</td>
<td>[90/0/+45/-45]$_{4S}$</td>
<td>18550.51</td>
<td>20332.99</td>
<td>8.77</td>
</tr>
</tbody>
</table>

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

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

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

- **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

CT23E
Cell 2
1-30-06

Ultra Violet Degradation

UV Degradation of FRP Wrap
A Strategy of Accelerated Testing Methodology (ATM)

US Navy All Composite Patrol Boat

How much would the property degrade in 20 yrs?

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°F Temperature    M: Months

Vijay and GangaRao, 1999
Alkaline Sustained-load Test of E-glass/Vinyl Ester Composites with Nanoclay (CFC Data)

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

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.