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LOAD-BEARING FRP COMPOSITE PANEL SYSTEMS: PPROCESS DEVELOPMENT, MANUFACTURING, MODELING AND EVALUATION

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PRESENTATION OUTLINES

- **Process Development and Manufacturing vs. VARTM**
  - **- Pultrusion: GFRP, CFRP**
  - **- High temperature resin infusion: GFRP**
- **Mechanical Properties of FRP Laminates**
  - **- Tensile and flexural**
  - **- Epoxy/Carbon vs. VE/Carbon**
- **Mechanical Properties of FRP Sandwich Panels**
  - **- Shear**
  - **- Bending**
  - **- Joint efficiency**
  - **- FE Modeling**
- **Conclusions - Performance and Cost Comparisons**

THE PULTRUSION PROGRAM

ONR Grant No. N00014-04/05-1-0050/96

Dr. Ignacio Perez, Program Officer

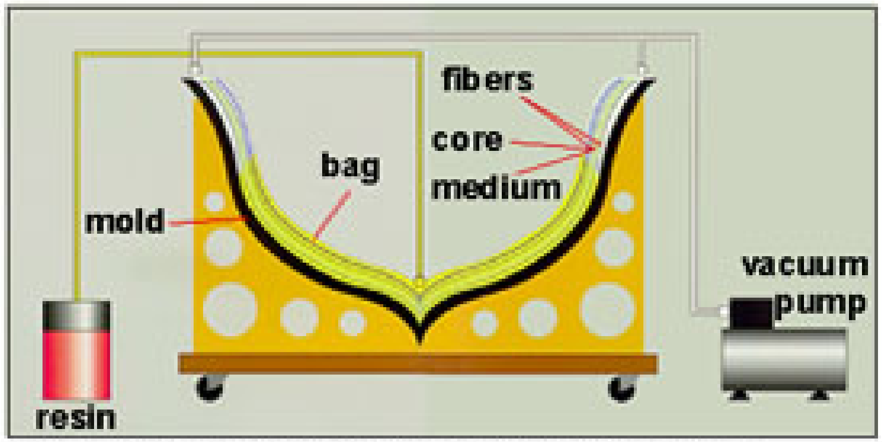
OBJECTIVE

To demonstrate feasibility of an automated pultrusion process for producing composite sandwich panels (4’ x 3.5” x unlimited length) which results in a product with improved mechanical performance and reduced production cost in relation to VARTM process

Target panel: 1/4” FRP face sheets with 3” balsa core

Vacuum-Assisted Resin Transfer Molding (VARTM)

SCRIMP SYSTEM SCHEMATICS



source illustration from Hardcore DuPont Composites

Boat Hull Manufacture

- Process developed and patented by Seamann's Composites
- Single-sided tooling
- Injection achieved through high-permeability surface layer to cause through-the-thickness flow

Seeman's Composite Resin Injection Molding Process (SCRIMP)

- **Hybrid of VARTM and vacuum bagging**

MILESTONES OF THE PROJECT

2004

- **1” sandwich panel (March 3, 2004), 300 sq ft**
- **3.5” sandwich panel (May 18, 2004), 220 sq ft**
  Each 200 sq ft, total 400 sq ft, No joint
- **2004 NSWC-VARTM panel (Aug 25, 2004)**
- **1.25” sandwich panel for bond improvement (Oct 12, 2004, 40 sq ft)**
  Note: Better properties thru pultrusion

2005

- **3.5” sandwich panel with joining edges**
  Two 400 sq ft runs (Jan 26 and June 28, 2005, total 800 sq ft)
- **2005 VARTM panel (May 31, 2005)**
- **Joint evaluation under bending and shear, 100% joint efficiency**

2006

- **3.5” carbon/vinyl ester sandwich panels**
  Two runs, 300 sq ft (June 23 and Sept 19, 2006))
- **FE analyses**
  Orthotropic 3D Model, fully describing the panel’s static responses

2007

- **Carbon/vinyl ester vs. carbon/epoxy**
- **3.5” glass/vinyl ester sandwich panels – High Temp Infusion Process**
  80 sq ft (Sept 19, 2007))
- **FE analyses**
  Full scale panel modeling, joint modeling

MATERIALS AND FABRIC CONFIGURATION

	2005 Pultruded GFRP	2006 Pultruded CFRP*	2005 VARTM GFRP	2007 HT Infused GFRP
Fabric Layers	6	6	10	5 + 1
Weight (oz/sq yd)	40	28	24	46.6 + 24
Total Weight	240	168	240	257
Type	quadaxial stitched	quadaxial stitched	woven roving	quadaxial + 0/90
Percent 0	33	21.4	30	30
Percent 90	27	21.4	30	30
Percent + 45	20	28.6	20	20
Percent - 45	20	28.6	20	20
Resin	Derekane 510A-40	Derekane 510A-40	Derekane 510A-40	Derekane 510A-40
Core	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf	Baltek D100 ~9.5 pcf

* Toray T700SC /12K / FOE carbon fabric

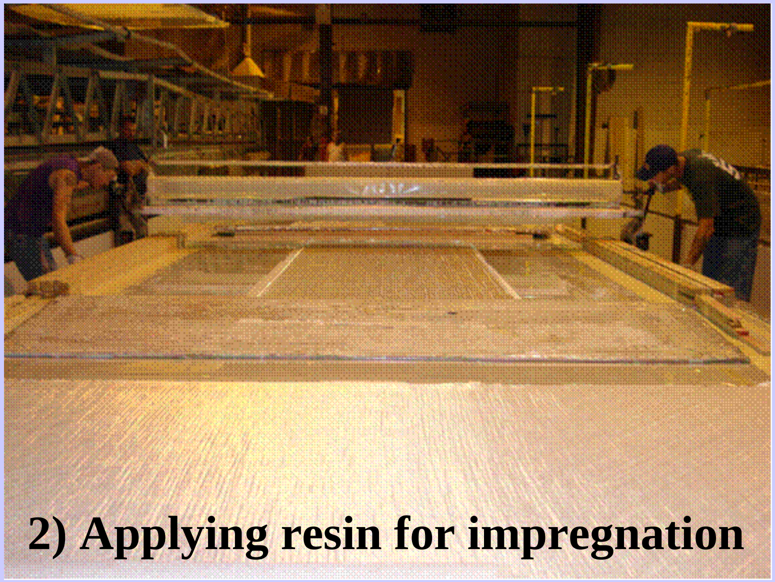
PULTRUSION OF GFRP PANEL -2004

PULTRUSION OF GFRP PANEL -2005

PULTRUSION OF CFRP PANEL -2006

High Temperature Resin Infusion Process -2007


1) Placement of fabric


2) Applying resin for impregnation


3) Placement of core panel


4) Top moving oven in position

MANUFACTURING PROCESS EVALUATION

- **VARTM**
  - **+ Low void content**
  - **+ Low One-sided tooling cost**
  - **+ Large-scale structural parts**
  - **+ Design flexibility for complex shapes**
  - **- Labor intensive**
  - **- High production cost**
  - **- Limit with room temperature curing**
  - **- Difficulty with epoxy due to its high viscosity**
  - **Good for large complex shapes (VE)**

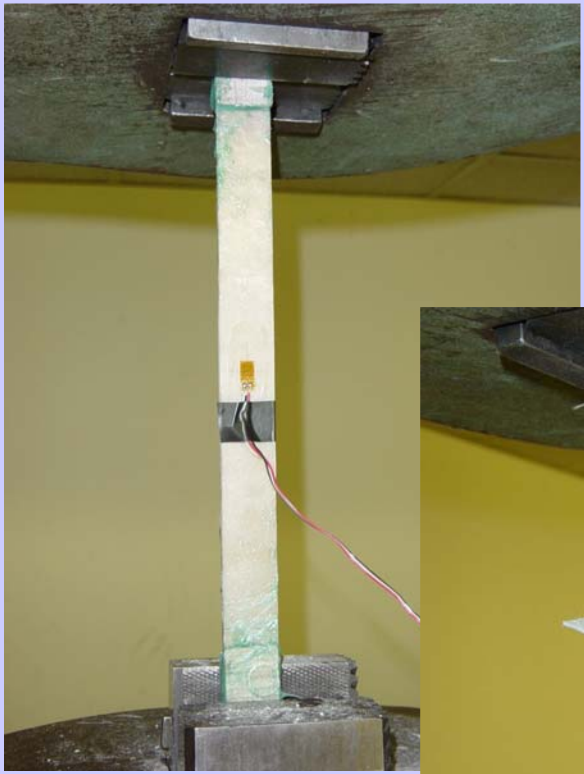
- **Pultrusion process**
  - **+ A highly automated continuous process with good quality control**
  - **+ High FVF and strength structural shapes**
  - **+ High temp curing and high cure percent**
  - **+ Minimum fiber kinking**

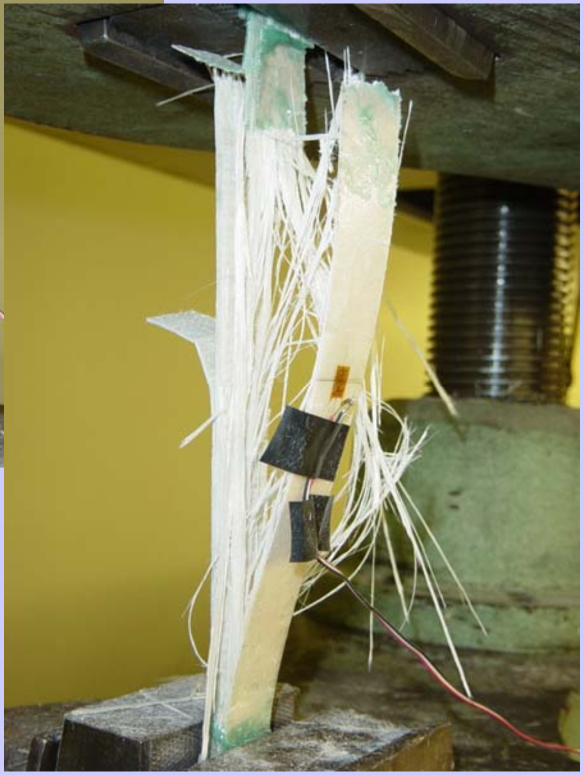
MANUFACTURING PROCESS EVALUATION (cont'd)

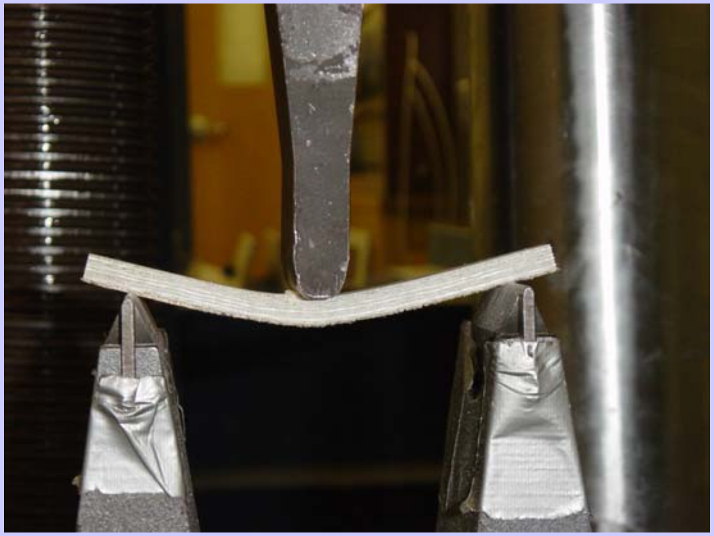
- **Pultrusion process**
  - **- Moderate tooling and capital equipment**
  - **- Limit with constant cross section and die dimensions (height and width)**
  - **- Difficulty with epoxy**
  - **Viable and cost effective than VARTM**
  - **High quality panel but width limitation**

- **High Temp Resin Infusion**
  - **+ Large size e.g. 10' x 60' platform operation**
  - **+ High temperature curing (up to 300F)**
  - **+ Zero scrap rate and low production cost**
  - **- Void content higher than VARTM and pultrusion**
  - **- Resin spread impregnation**
  - **Large size, flat, glass/VE or carbon/epoxy panel**
  - **Viable and even more cost effective than pultrusion**

TESTING OF FRP LAMINATES







FRP LAMINATES: FIBER VOLUME FRACTION

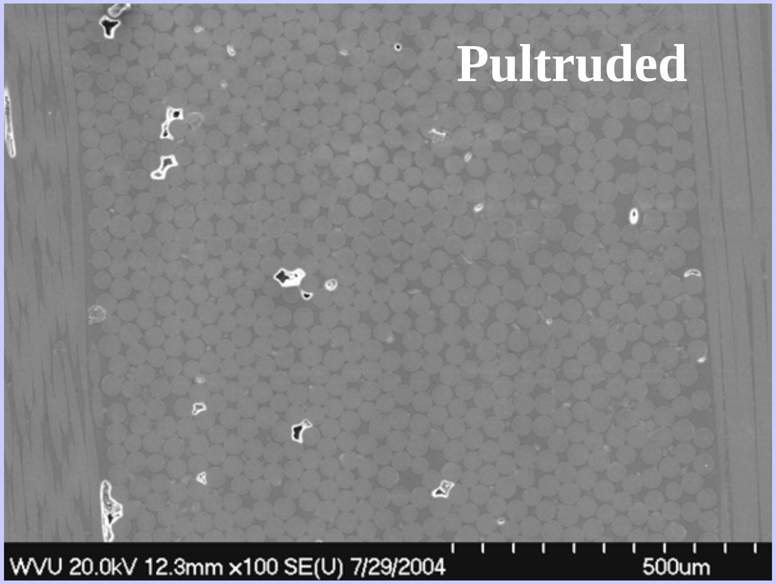
	Unit	2005 Pultruded GFRP	2006 Pultruded CFRP	2005 VARTM GFRP	2007 HT Infused GFRP
Fabric density	oz/sq yd	240	168	240	257
Face sheet thickness	inch	0.250	0.230	0.263	0.281
Fiber content by weight	%	70.5	65.1	63.5	67.7
Fiber content by volume	%	56.5	55.0	48.7	53.3

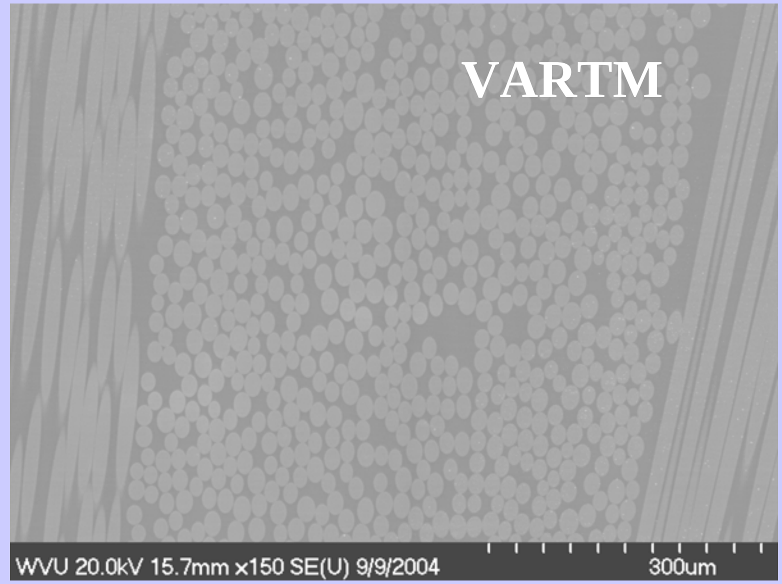
GFRP panel 7.80 lb/sq ft

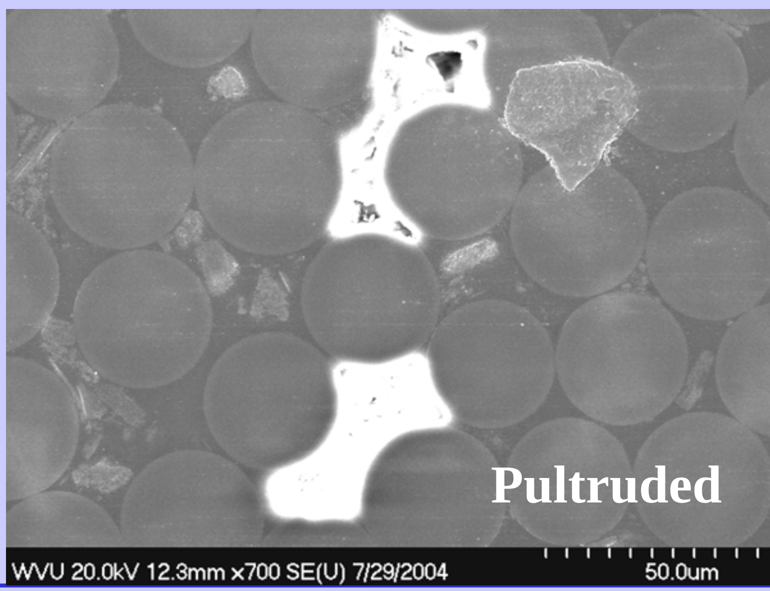
CFRP panel 6.60 lb/sq ft

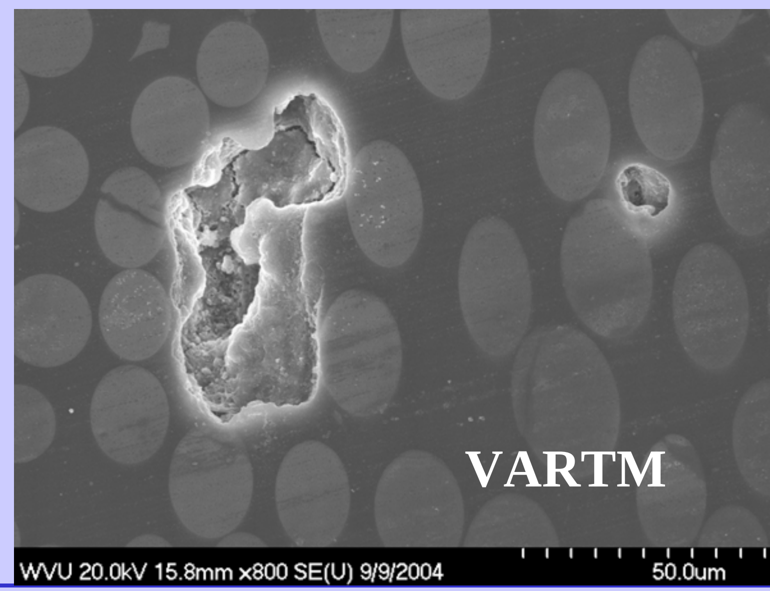
CFRP panel is 15-20% lighter than GFRP panel

SEM MICROGRAPHS OF FIBER/RESIN INTERFACE









FRP LAMINATES: TENSILE PROPERTIES

Note: modulus data are obtained from measured strains	Unit	2005 Pultruded GFRP	2006 Pultruded CFRP	2005 VARTM GFRP	2005 HT Infused GFRP
Tensile strength (LW)	ksi	52.17	65.92	43.52	43.96
Tensile strength (CW)	ksi	39.32	49.26	42.98	42.76
Tensile modulus (LW)	msi	3.24	5.25	2.83	3.11
Tensile modulus (CW)	msi	2.91	5.24	2.76	2.71

Conclusion: Pultruded GFRP is about 15-20% stiffer and stronger, in pull direction, than VARTM GFRP under tension; pultruded CFRP is 30-40% stronger and 60-70% stiffer than pultruded GFRP.

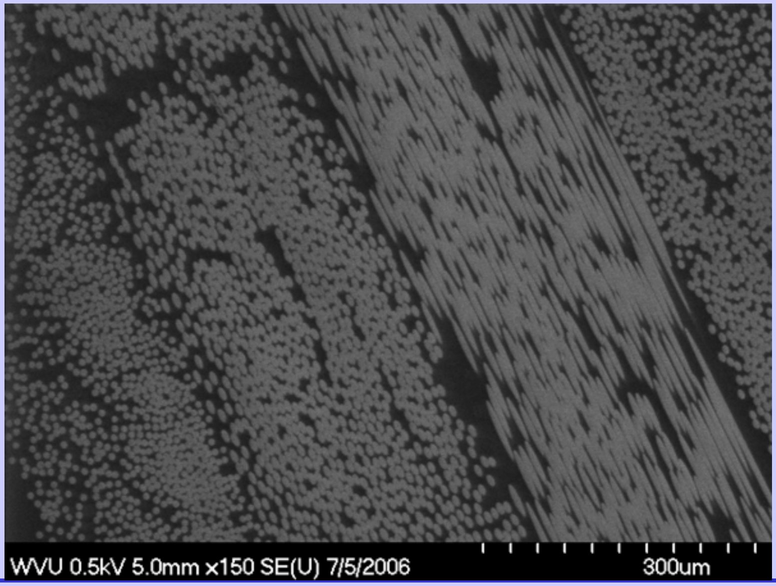
FRP LAMINATES: FLEXURAL PROPERTIES

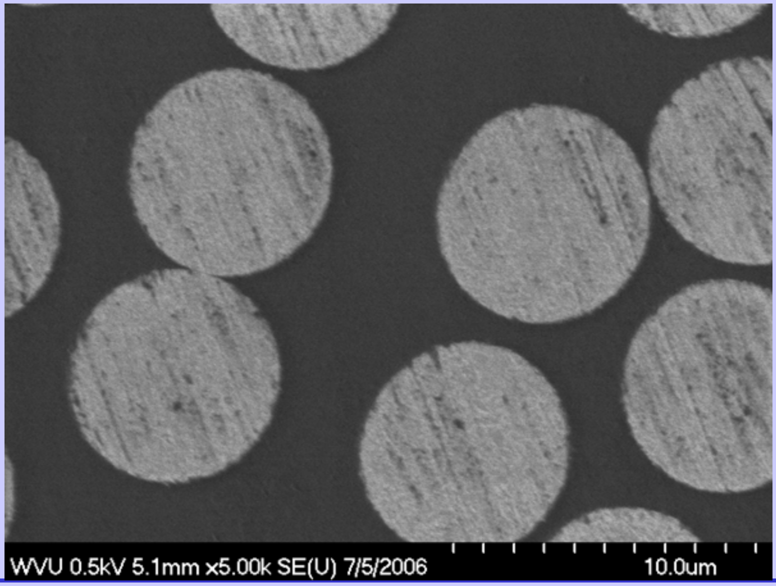
*** Different fabric architecture in CFRP and GFRP**

Note: modulus data are obtained from measured deflections	Unit	2005 Pultruded GFRP	2006 Pultruded CFRP	2005 VARTM GFRP	2007 HT Infused GFRP
Flexural strength (LW)	ksi	79.6	71.0	57.7	57.0
Flexural strength (CW)	ksi	56.0	50.4	46.7	55.7
Flexural modulus (LW)	msi	3.03	5.29	2.55	2.41
Flexural modulus (CW)	msi	2.20	4.66	2.14	2.39

Conclusion: Pultruded GFRP is about 20-40% stiffer and stronger, in pull direction, than VARTM GFRP under bending; pultruded CFRP is 75-100% stiffer than pultruded GFRP.

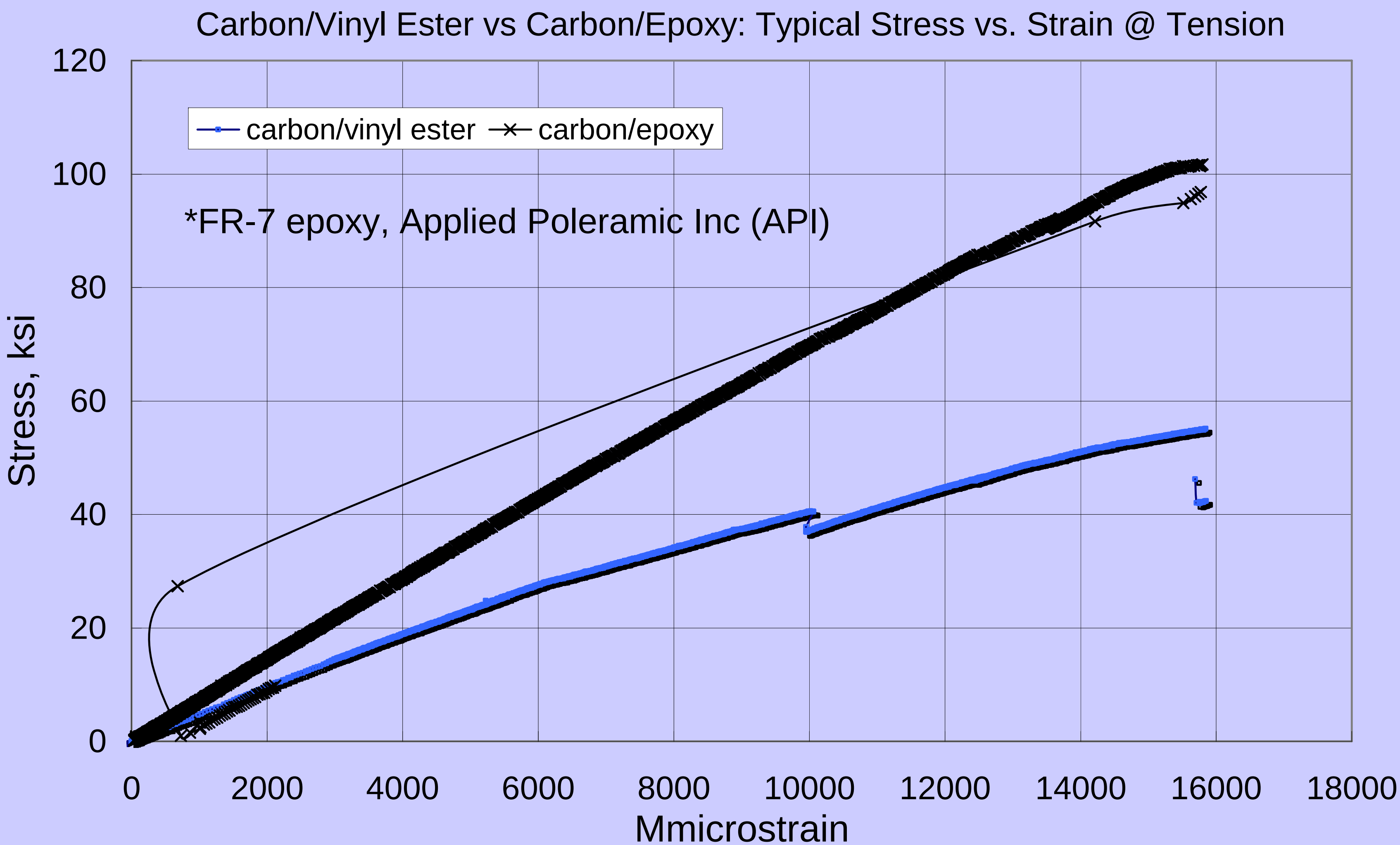
CARBON SIZING/VE COMPATIBILITY ISSUE?





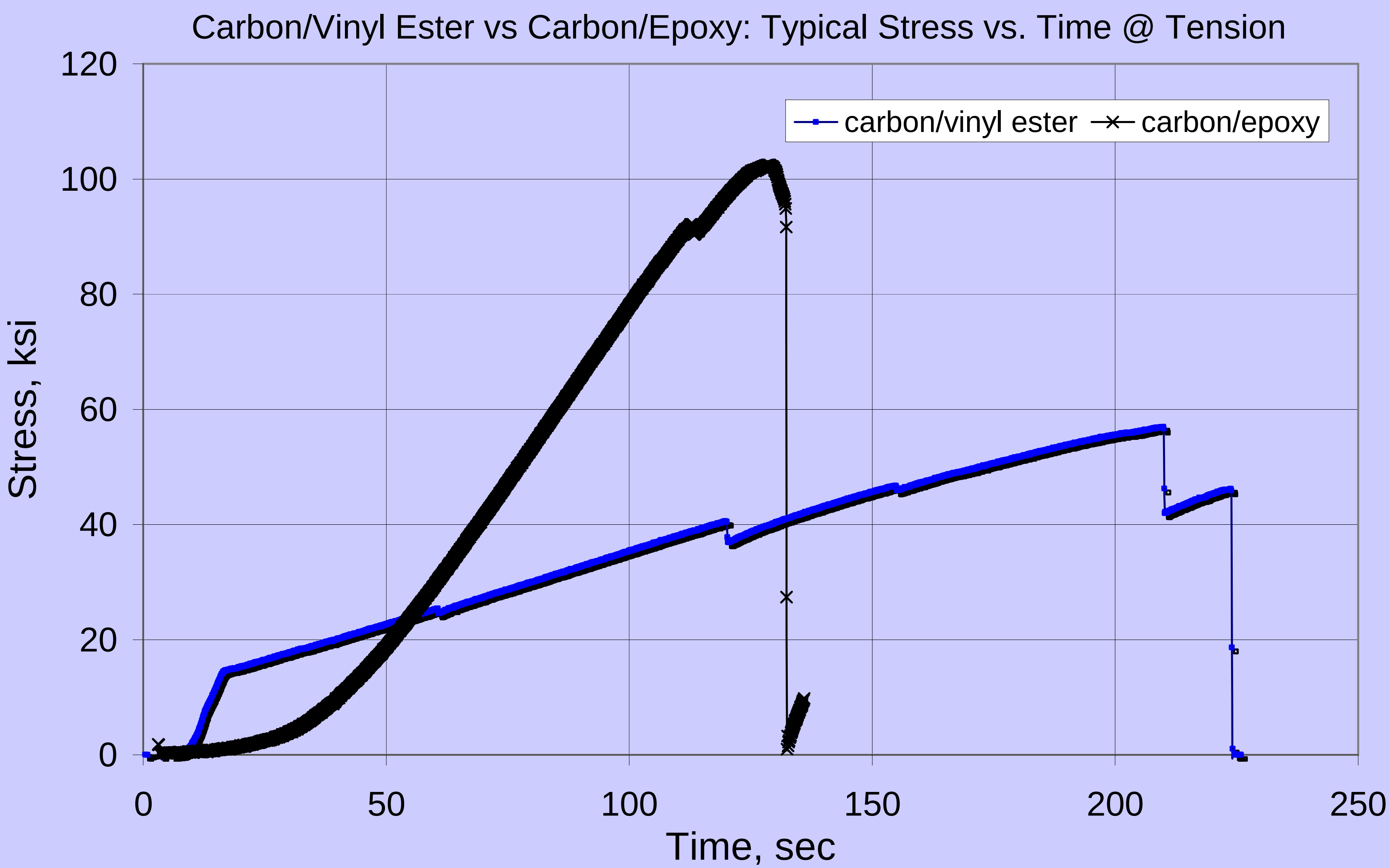
TENSION TEST: STRESS- STRAIN

Carbon /VE vs. Carbon/Epoxy

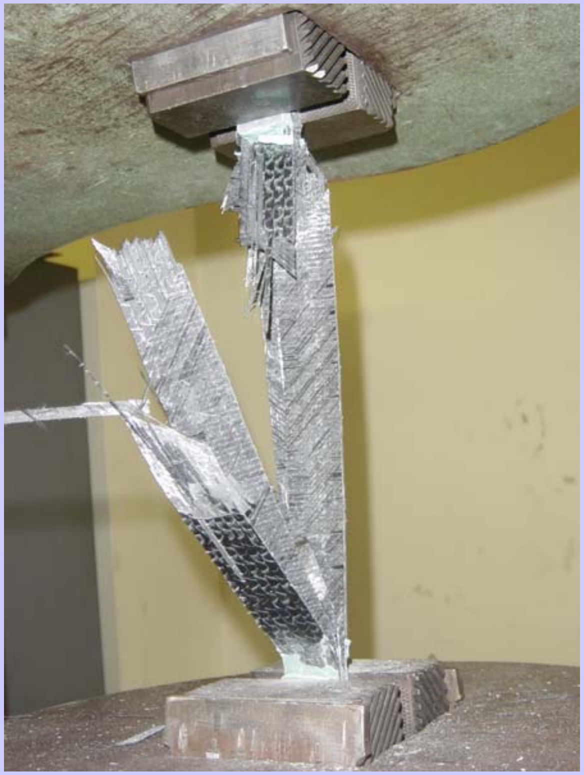


TENSION TEST: STRESS- TIME

Carbon /VE vs. Carbon/Epoxy



TENSION TEST: SOME FAILED SPECIMENS

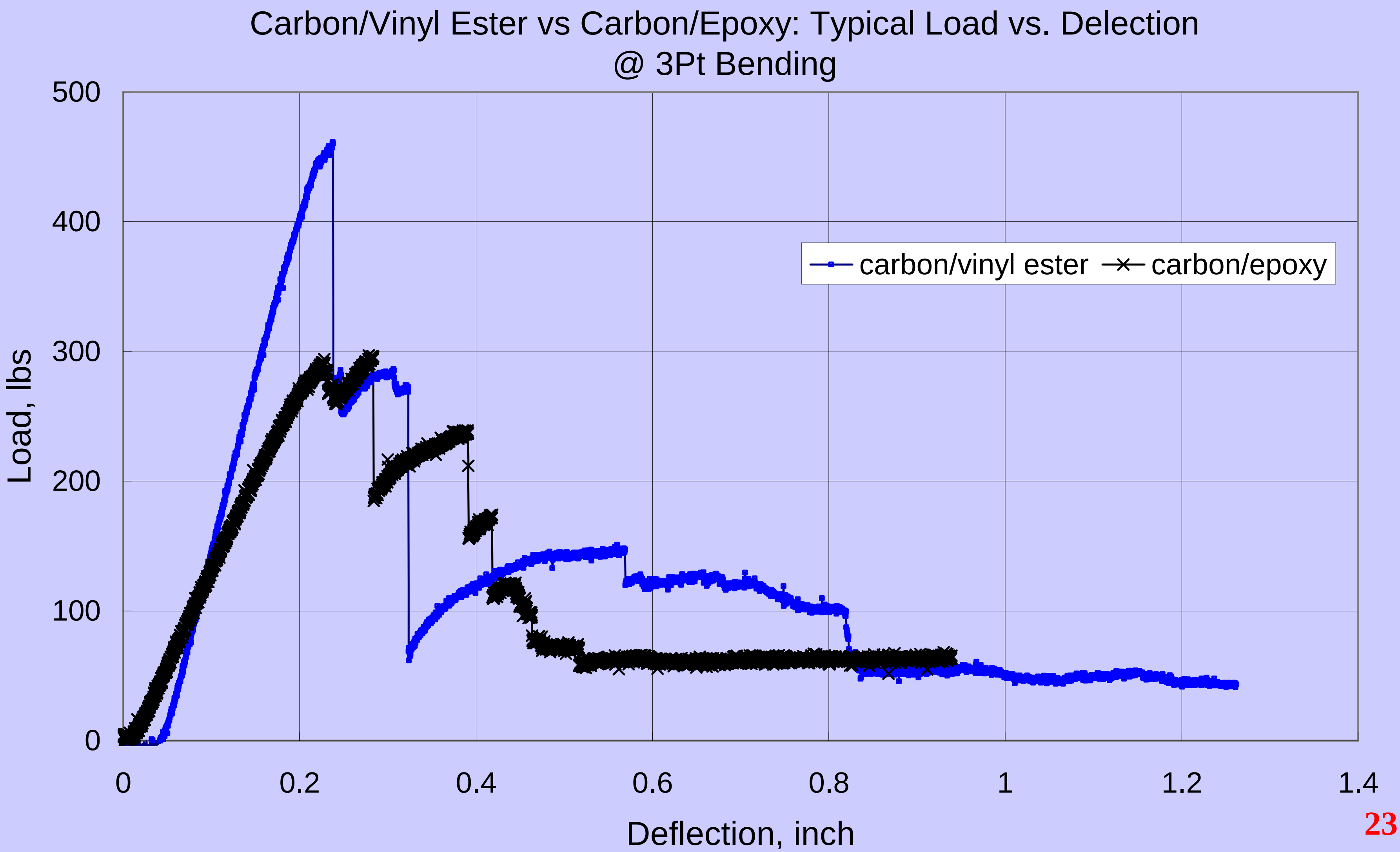


Pultruded Carbon/VE

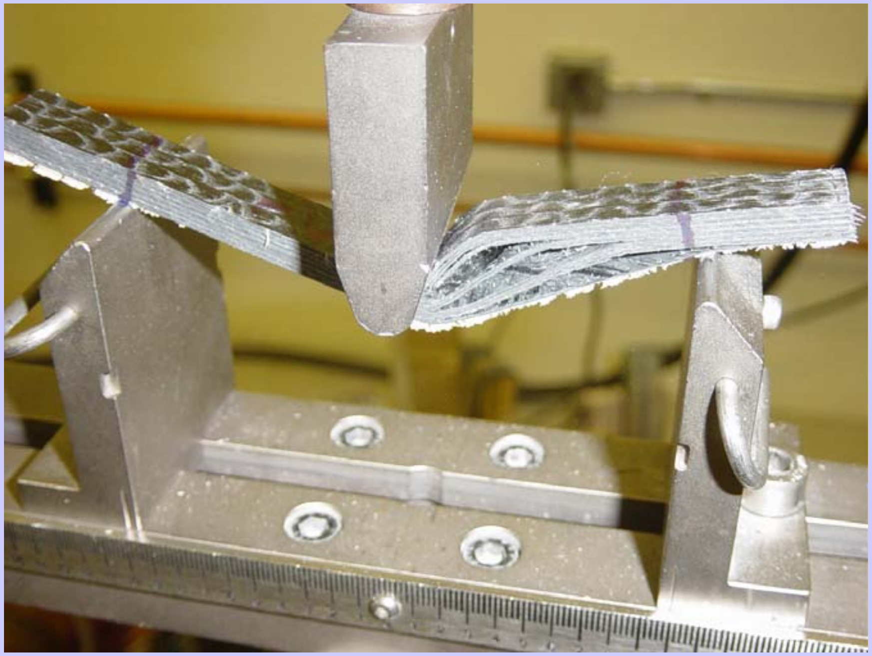
Compression made Carbon/Epoxy

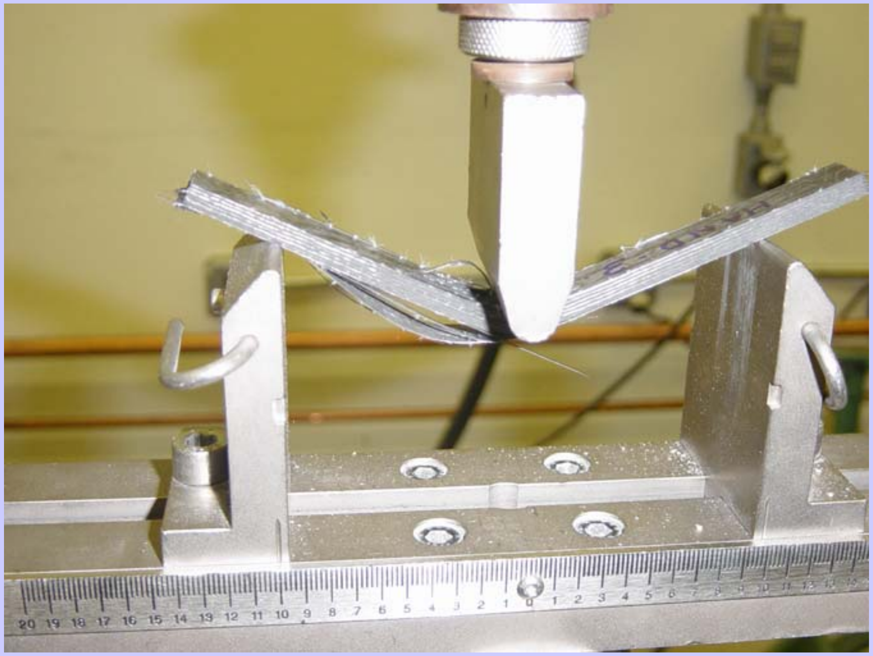
BENDING TEST: LOAD- DEFLECTION CURVE

Pultruded Carbon /VE vs. Compression molded Carbon/Epoxy



BENDING TEST: FAILED SPECIMENS



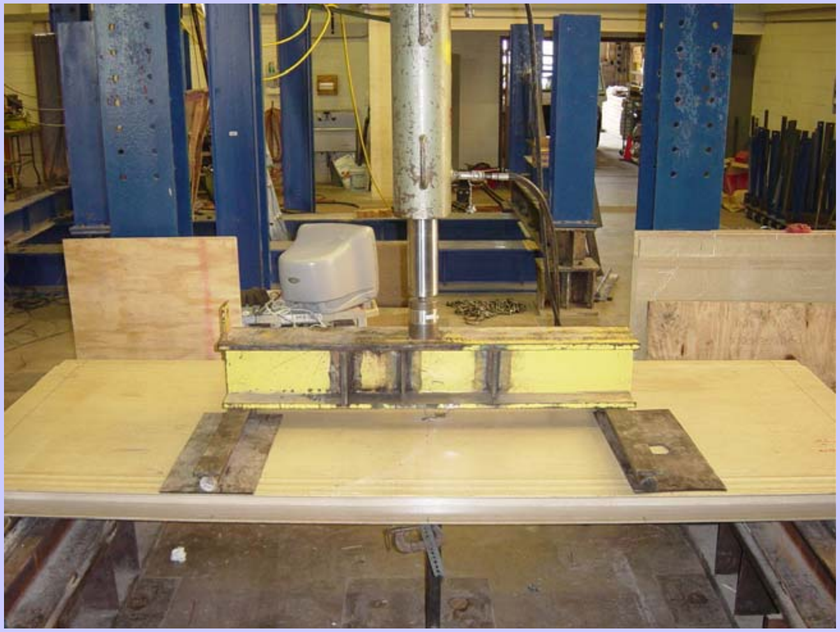


Pultruded Carbon /VE vs. Compression molded Carbon/Epoxy

The high performance of carbon fiber has not translated into a proportionate property improvement of CFRP composites over GFRP, due to the carbon sizing incompatible with VE. Carbon/epoxy should be recommended.

PANEL LEVEL TEST

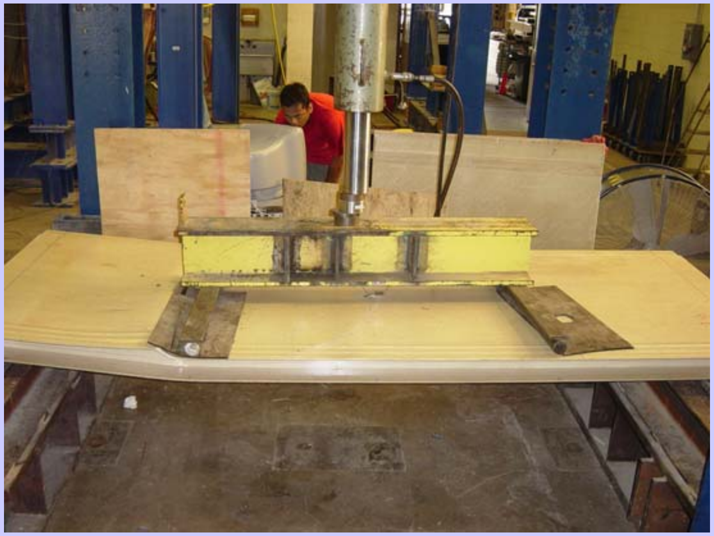
PULTRUDED GFRP VS VARTM PANEL*

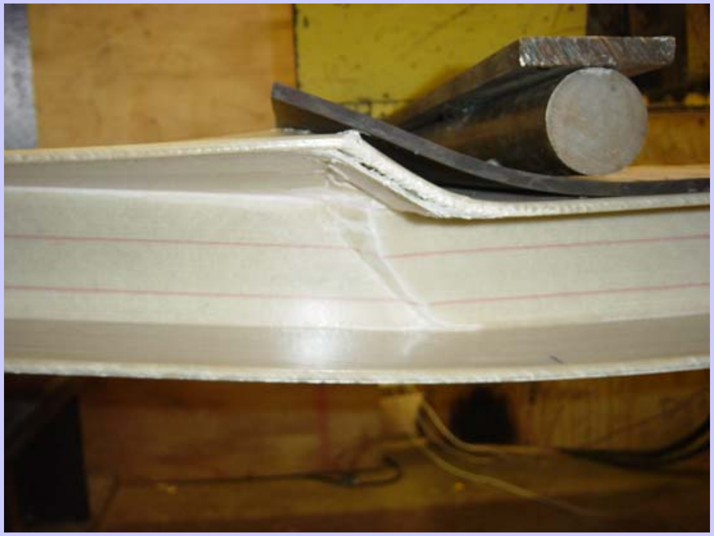


Panel: 4' x 10'
Span: 100"
Test: 4 point loading with a load span of one-half of the support span

*** 200 sq ft of sandwich panels thru VARTM process were supplied by NGSS in 2005.**

PULTRUDED GFRP VS. NGSS VARTM (4' x 10'): After test





SANDWICH PANEL BENDING PROPERTIES:

4’ x 10’ panels / 100” span, 4pt bending

	Unit	2005 Pultruded GFRP	2006 Pultruded CFRP	2005 VARTM GFRP
Failure load/unit width	lbs/in	1331	1511	1120
Load/defl. slope	lbs/in	15757	23512	14234
Failure strain	micro	5944	3982	6020
Balsa stress at failure	psi	204.7	232.5	172.2
FRP stress at failure	ksi	22.05	25.04	17.63
Modulus from strain	msi	4.06	6.48	2.96
Modulus from deflect.	msi	4.27	6.27	3.06

Failure is initiated by shear failure at balsa core.

Conclusion: Pultruded GFRP panel is about 15-20% stronger and stiffer than VARTM. Pultruded CFRP panel is about 50-80% stiffer than GFRP panel.

BENDING OF SMALLER PANELS: PULTRUDED GFRP VS. NGSS VARTM

Panel: 12” x 8’ **Span:** 80”

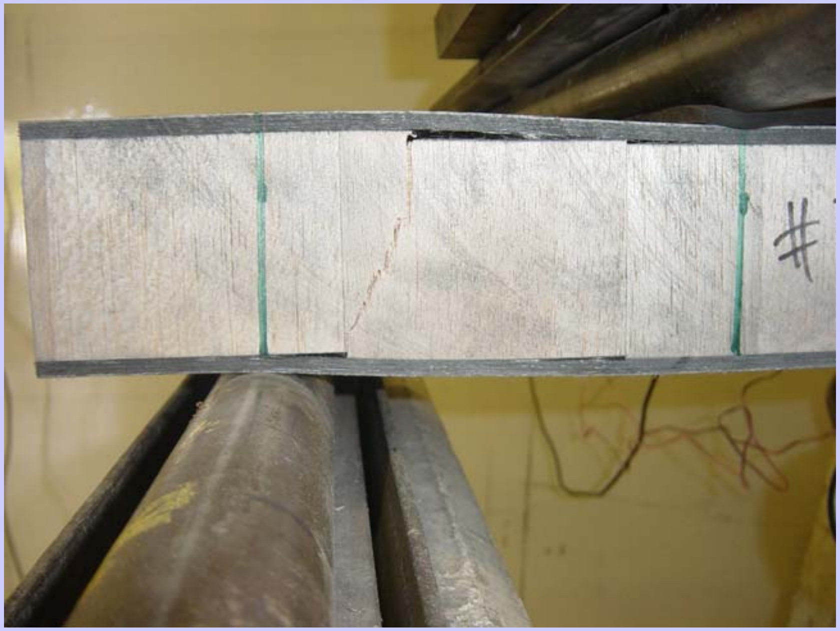
Test: 4 point loading with a load span of one-half of the support span

BENDING PROPERTIES: GFRP VS. CFRP PANEL

12” x 96” 80” span, 4pt bending	2005 Pultruded GFRP	2006 Pultruded CFRP	2005 VARTM GFRP	2007 HT Infused GFRP
Failure load P lbs/ inch	1378	1414	1261	1130
Failure micro strain	6000 top 5726 bot	3348 top 3448 bot	5695 top 5031 bot	4647 top 4871 bot
Max deflection inch	2.44	1.47	-	1.92
Bending stress ksi	18.63	18.74	15.90	14.98
Bending modulus, msi	3.03	5.40	2.76	3.10
Core shear stress, psi	218.7	217.5	194.1	173.8

Note: **Strong bond between balsa wood core and FRP face sheet is observed**

SHORT BEAM 'SHEAR' TESTING OF CFRP SANDWICH PANELS



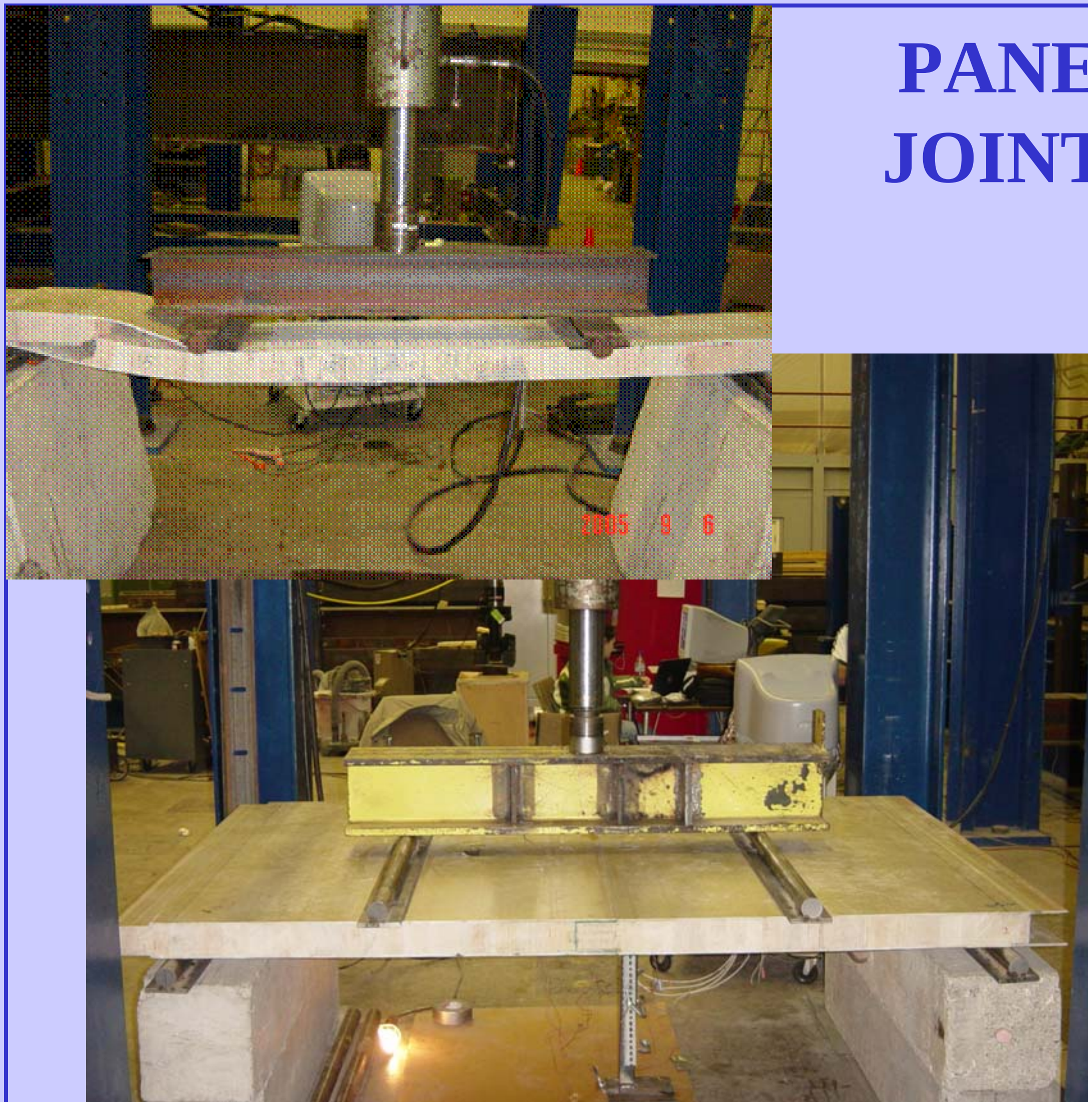
Panel: 12" x 36"   Span: 27"

Test: 4 point loading with a load span of one-half of the support span

This set up for smaller panels allows for longitudinal and transverse testing

- **Shear failure at balsa core**
- **Both GFRP and CFRP panels are identical in performance**

PANEL JOINT AND JOINT EFFICIENCY



Panel: 5' x 8' **Span:** 80"

Test: 4 point loading with a load span of one-half of the support span

A Pultruded Joint

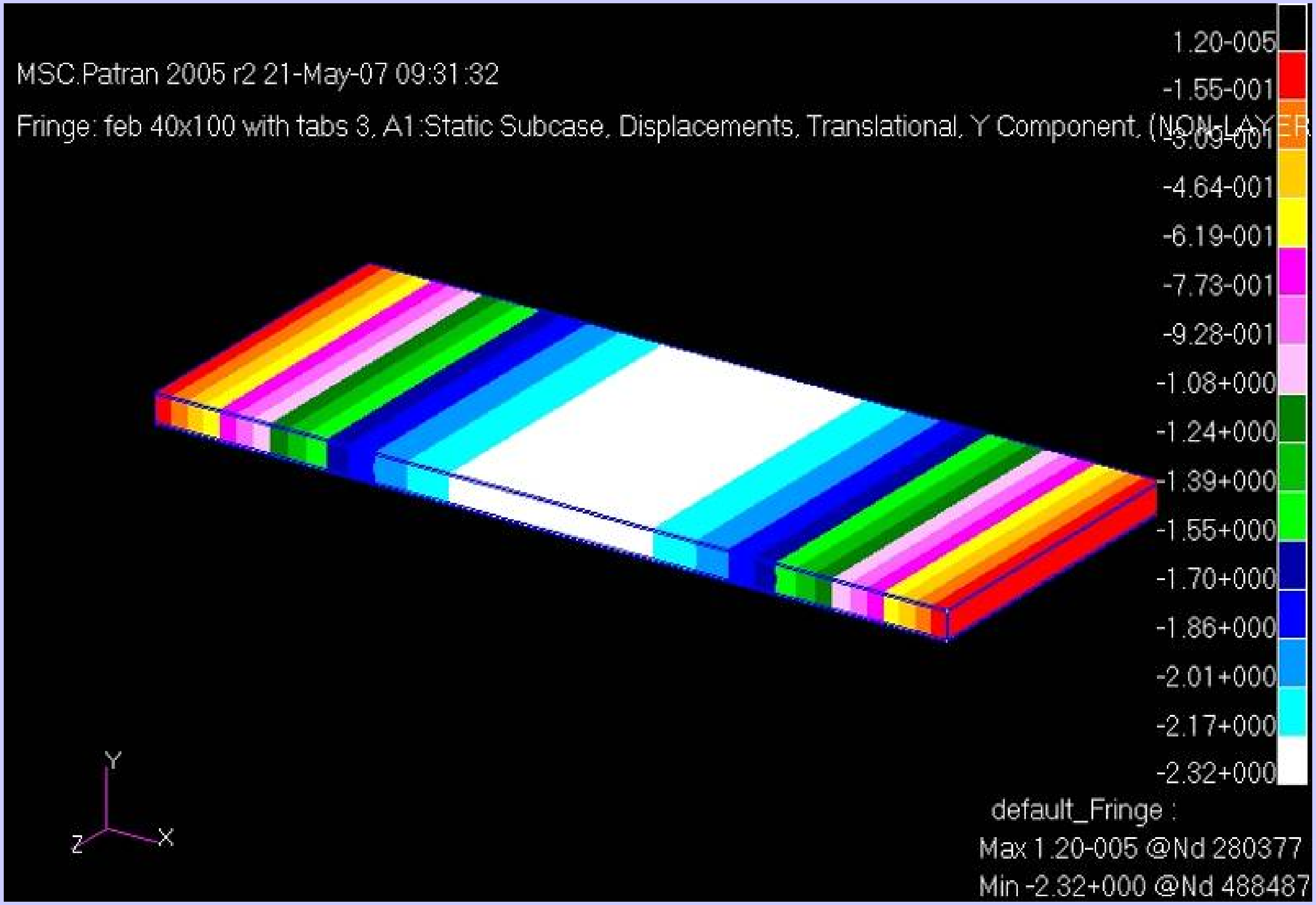
A VARTM Joint

JOINED SANDWICH PANEL PROPERTIES

	Unit	2005 Pultruded GFRP	2005 VARTM GFRP
Bending at a span of 80" for 12" wide panel sections ("True Bending")			
Failure load/unit width	lbs/in	1378 (no joint) 1433 (joint)	1261 (no joint) 1444 (joint)
Failure strain	micro	5726 (no joint) 6774 (joint)	5695 (no joint) 5916 (joint)
Modulus from load/strain slope	msi	3.03 (no joint) 3.20 (joint)	2.76 (no joint) 3.08 (joint)
Joint efficiency	%	100 (No joint failure)	100 (No joint failure)
Bending at a span of 27" for 12" wide panel sections ("Shear Dominance")			
Failure load/unit width	lbs/in	1613 (no joint) 1674 (joint)	1675 (no joint) 1523 (joint)
Failure strain	micro	1977 (no joint) 2096 (joint)	1912 (no joint) 1424 (joint)
Modulus from load/strain slope	msi	3.47 (no joint) 4.53 (joint)	3.28 (no joint) 3.96 (joint)
Joint efficiency	%	100 (No joint failure)	100 (No joint failure)

60 joints (in 4 batches) designed, fabricated, and tested to arrive at 100% efficiency under shear and bending

FINITE ELEMENT MODELING OF FRP COMPOSITE SANDWICH PANELS



Deflection contours by 3D orthotropic solid model for 40”x100” CFRP panel

MODEL PREDICTIONS IN COMPARISON WITH EXPERIMENTAL VALUES

12”x 80” and 40”x 100” CFRP panels

Panel Dimensions		Failure load (lbs)	Centre Deflection (in.)	Bending Stress (ksi)	Core Shear Stress (psi)
12” x 80”	Experimental	13774	1.39	15.29	177.50
	Sandwich beam theory		1.39	15.21	176.58
	3D Orthotropic Solid Model		1.32	15.14	176.21
40” x 100”	Experimental	55745	2.34	23.09	214.40
	Sandwich beam theory		2.38	23.09	214.40
	3D Orthotropic Solid Model w/o caps		2.39	22.99	216.21
	3D Orthotropic Solid Model with 3” caps		2.32	22.96	208.14
	3D Orthotropic Solid Model with 3.5” caps		2.32	22.96	208.14

CONCLUSIONS

- **Glass/VE**
  - **Pultruded panel is ~15-20% stronger and stiffer, and 50% lower in cost than VARTM panel**
  - **HT infused panel performs as well as VARTM panel, but costs a third of VARTM panel**
  - **100% joint efficiency**

- **Carbon/VE**
  - **Pultruded CFRP panel is ~50-100% stiffer, 10-15% stronger and 15-20 % lighter than pultruded GFRP panel**
  - **CFRP property improvement over GFRP not commensurate to cost increase (Carbon ~$15 /lb fiber, $30/ lb fabric vs. Glass ~$0.70/lb, $1.5-2.0/lb fabric)**
  - **Carbon/epoxy is strongly recommended, due to compatibility and durability issues with carbon/VE**

CONCLUSIONS (cont'd)

- **Pultrusion process**
  - **Viable and cost effective than VARTM**
  - **High quality panel**

- **High Temp Resin Infusion**
  - **Large size, flat, glass/VE or carbon/epoxy panel**
  - **Viable and even more cost effective than pultrusion**

- **Finite element modeling of panel response**
  - **3D orthotropic solid model (3D geometry + orthotropic material properties)**
  - **Viable for accurate predictions of deflection, bending stress, and shear stress**
  - **~100% match between predictions and experimental data**