Public Meeting

Overview of Limited Confirmatory Testing Program on Carbon Fiber Reinforced Plastic (CFRP) Repair System at Emc^2

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Composite Repair Technical Information Exchange

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  - Mr. Rick Turk, NUMARK, Task Manager

Outline

- ***Effective factor of safety for CFRP repair system***
- ***Coupon Testing***
  - ***Single-ply tensile tests***
    - ***Characteristics values (ASTM D7290, A Basis and B Basis)***
    - ***Effect of tensile specimen width***
    - ***Effect of fiber misalignment***
    - ***Effect of temperature (125F, 140F, 175F)***
  - ***Multi-ply tensile tests***
    - ***Characteristics values (ASTM D7290, A Basis and B Basis)***
    - ***Strength reduction factor on multi-ply laminates***
  - ***Bond Strength***
    - ***Double lap shear strength***
    - ***Pull-off test***
  - ***Durability Testing***
    - ***Material adjustment factors at 140F under salt-water condition***
    - ***Tensile, flexural, double lap shear and pull-off strength***
- ***Watertightness test (future test - ~March 2020)***
- ***Full-scale hydrostatic test (future test – late summer 2020)***

Effective Factor of Safety

- ***Per ASME Boiler & Pressure Vessel Section XI Code Case N-871-1, the allowable design stress value is obtained as,***

$$S_h = \frac{S_u}{10}$$

Where S_u is the Characteristic value of ultimate strength of single-ply CFRP lamina

- ***So, the apparent factor of safety (FS) is 10.***
- ***However, ultimate strength of CFRP is greatly affected by several degradation mechanisms as well as some other design considerations***
- ***So there are several strength reduction factors that should be included in determining the effective FS***
- ***In our PVP2018 paper*, a minimum effective FS of 3.5 is recommended to be used for CFRP repair to at least match with ductile steel's FS***

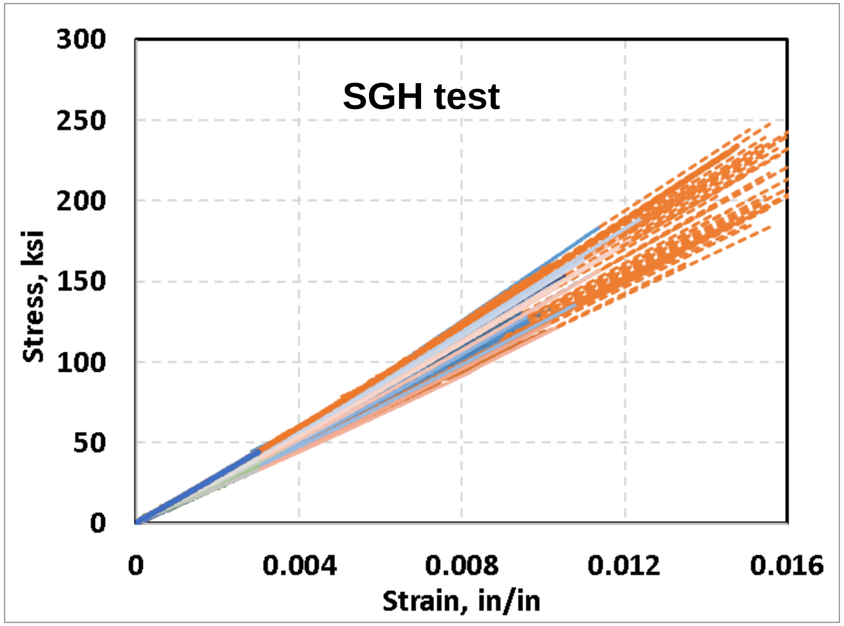
$$Effective\ FS = 10.0\ \times All\ strength\ reduction\ factors$$

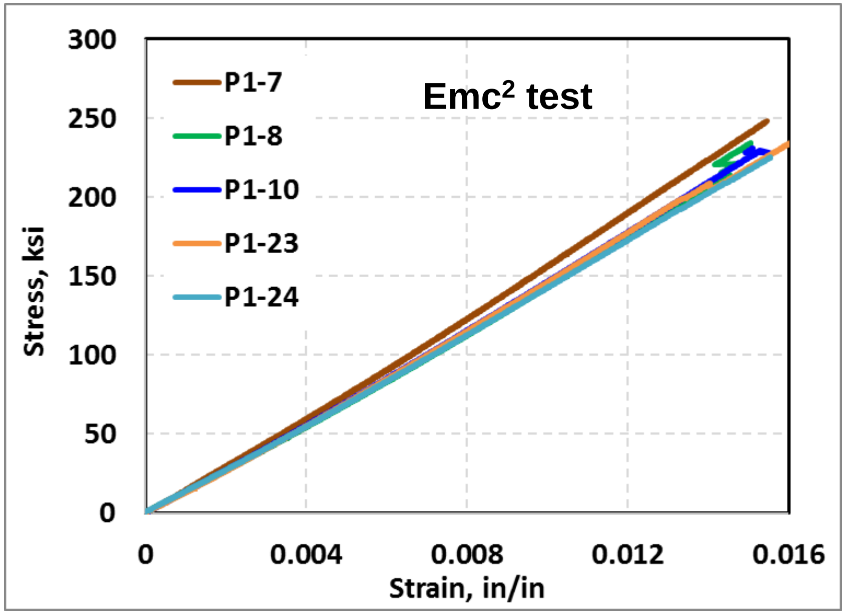
* M. Uddin, P. Krishnaswamy, C. Basavaraju, K. A. Manoly, PVP2018-84972, ASME 2018 Pressure Vessel and Piping Conference, Prague, Czech Republic.

Various Strength Reduction Factors

Various strength reduction phenomena	Required tests to determine the strength reduction factors	Current status of tests at Emc^2
Difference in Characteristic values of ultimate strength of single-ply CFRP lamina (ASTM D7290 vs A basis)	Tensile tests on single-ply CFRP lamina	Confirmatory tests completed – preliminary results available
Effect of misalignment angle	Tensile tests on off-axis single-ply test specimens	Confirmatory tests completed – preliminary results available
Effect of temperature (RT vs 125F)	Tensile tests on single-ply CFRP lamina at RT and 125F	Confirmatory tests ongoing
Strength reduction in multi-ply laminates	Tensile tests on multi-ply laminates with 2,3 and 4 layers	Some confirmatory tests are completed – others ongoing
Time effect factor	Available in literature and ASME CC N-871-1	No tests planned
Long-term material degradation factors on ultimate strength and modulus	Durability testing on single-ply and multi-ply CFRP laminate at various environments	Confirmatory tests ongoing

Single-Ply Tensile Tests

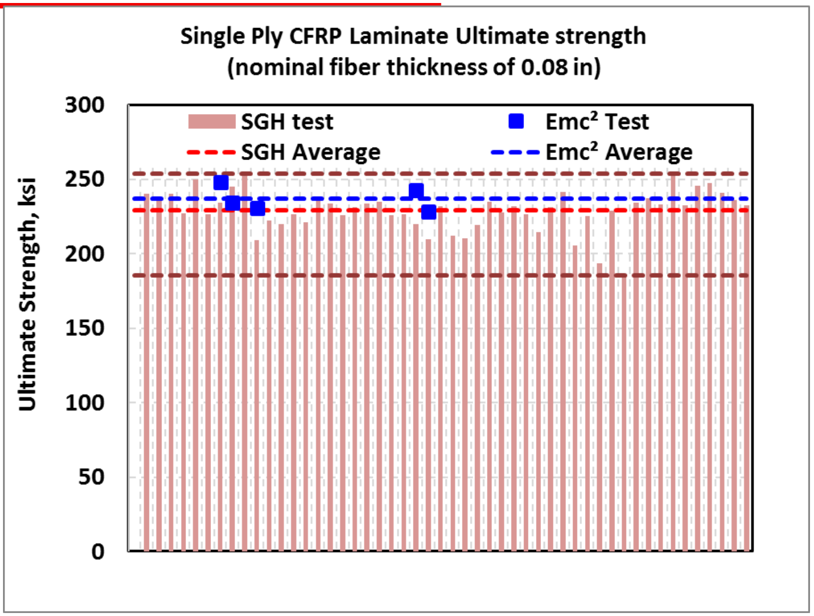




- *Tensile specimens were prepared by Structural Technologies under a Purchase Order from Emc²*
- *50 tensile tests on single-ply were conducted at Simpson Gumpertz & Heger (SGH) under a Purchase Order from Emc²*
- *Confirmatory tensile tests were conducted at Emc² lab*

Single-Ply Tensile Tests

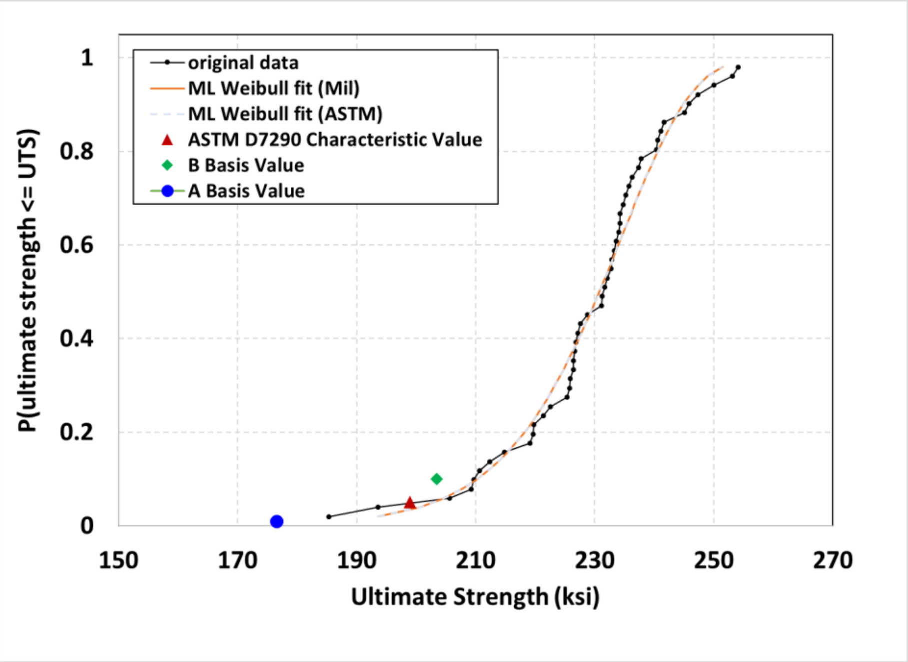
Properties	SGH Test		Emc²Test		% Difference
	Average	COV	Average	COV	Emc²/SGH
Ultimate Strength, ksi	229.0	6.0%	236.80	3.5%	3.4%
Modulus, ksi	14.18	3.6%	13.93	4.6%	-1.8%



- *Ultimate strengths of all tensile tests conducted at Emc² lab are within the range of all 50 tests conducted at SGH*
- *The average ultimate strength of 5 tests at Emc² is slightly higher than that of 50 SGH test*
- *The average moduli are very similar*

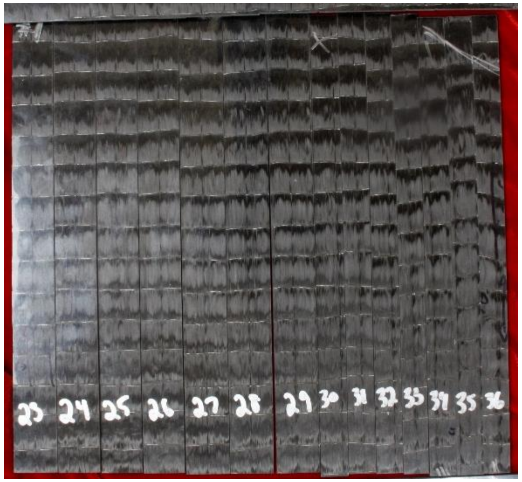
Characteristic Values of Ultimate Strength

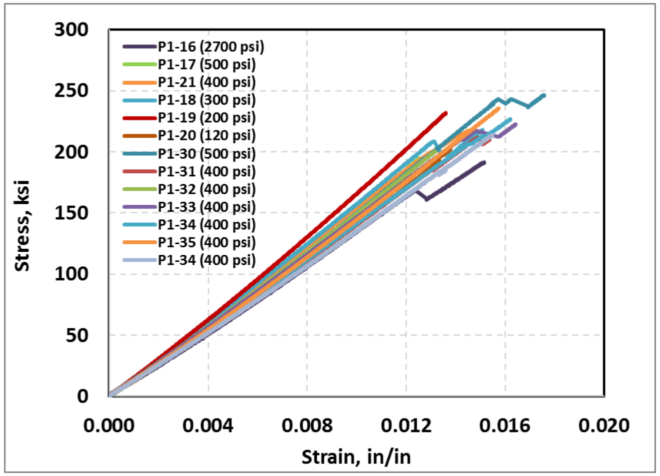
Methods	Characteristic Values of Ultimate Strength, ksi	Difference with CC-N871
ASTM D7290 (CC N-871)	198.9	-
A Basis	176.5	-11%
B Basis	203.5	2%

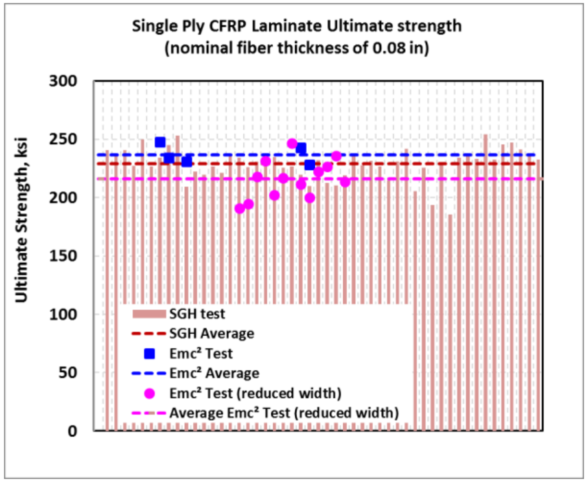


- *Characteristic value of ultimate strength (allowable strength) using CC-N871 recommended method ASTM D7290 (5th percentile with 80% confidence) is very close to the B basis value (10th percentile with 95% confidence)*
- *However the A basis value (1st percentile with 95% confidence) is 11% lower than Code recommended value*

Effect of Specimen Width







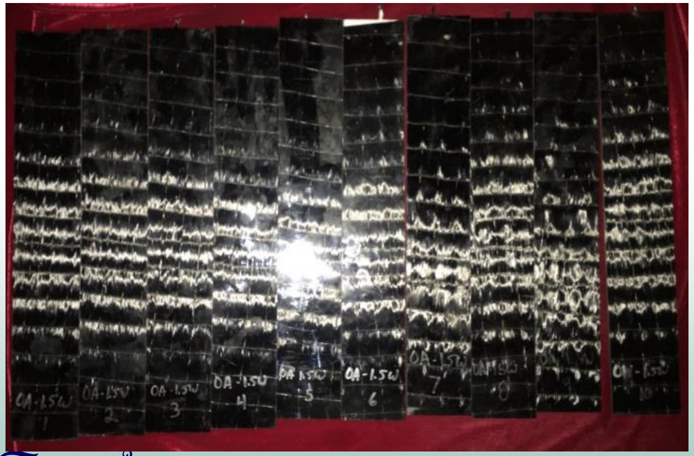
Properties	Full Width		Reduced Width		% Difference Reduced/Full Width
	Average	COV	Average	COV	
Ultimate Strength, ksi	236.8	3.5%	216.30	7.6%	-8.7%
Modulus, ksi	13.93	4.6%	13.92	6.5%	-0.1%

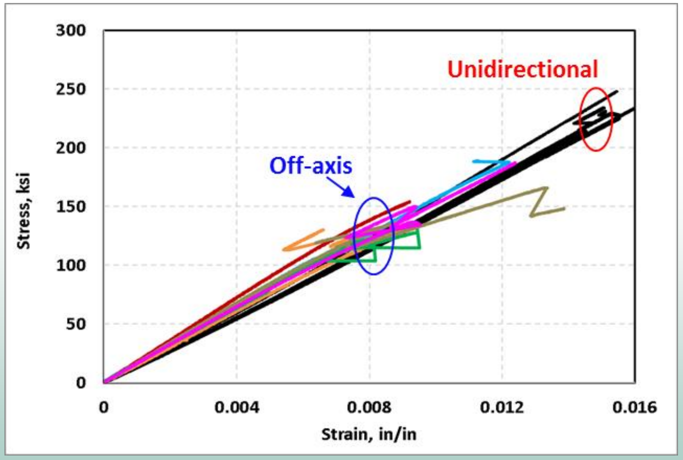
- ***Reduced width specimens showed about 8.7% reduction in strength as compared to their full-width single ply laminate***

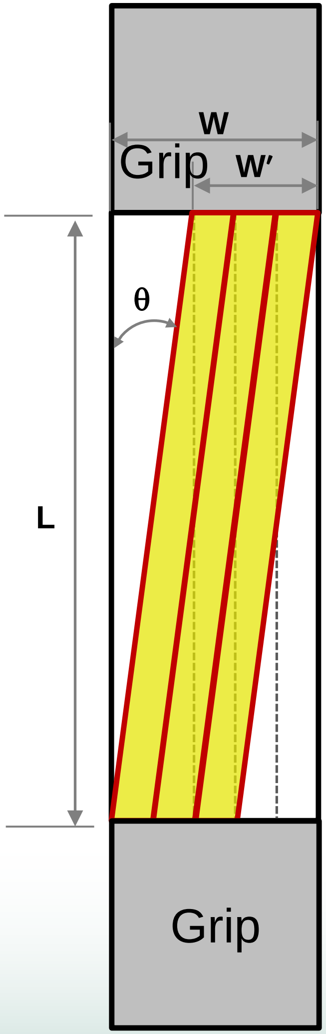
Effect of Misalignment Angle

- Code Case N-871 allows ~4.7^{0} misalignment angle (1 in./ft)
- Prepared tensile specimens with 4.7^{0} misalignment angle with the width, W
- As fibers are continuous in the actual pipe repair, equivalent width (W') should be used to calculate the strength
- The full width, W is chosen such that W' is similar to width of unidirectional (0^{0}) tensile specimen
- Equivalent width for continuous fiber between grips, W'

$$W' = W - L \times \tan\theta$$

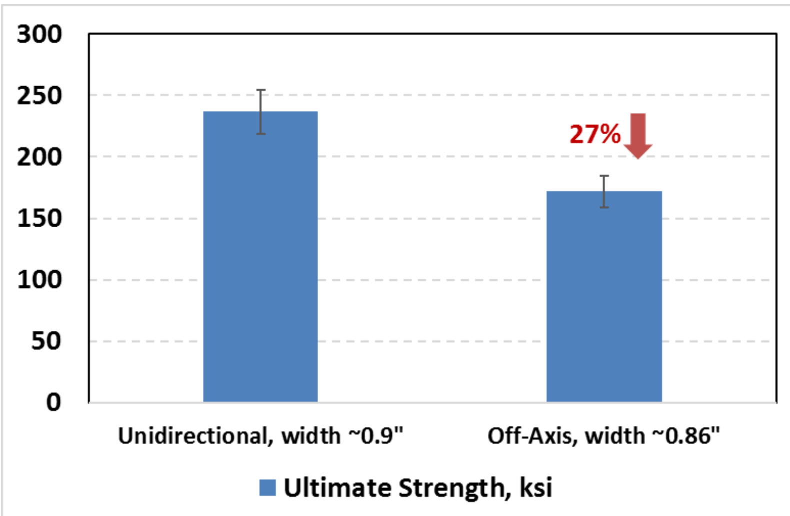


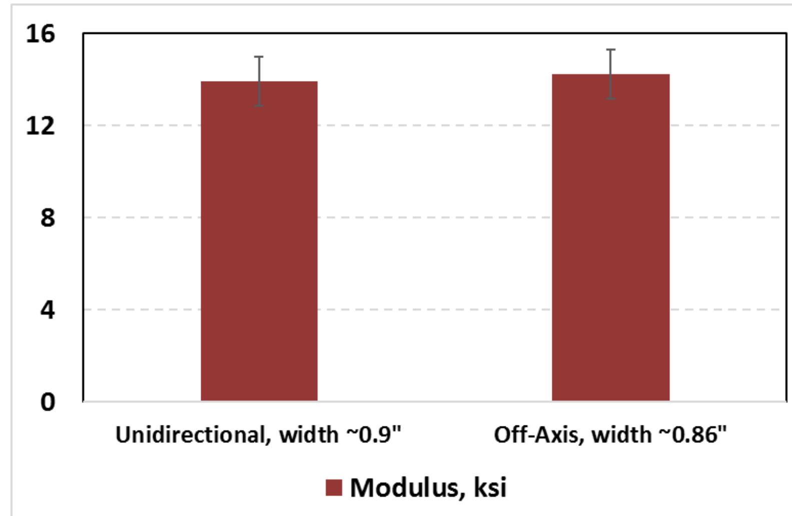




Effect of Misalignment Angle

- Due to ~4.7^0 misalignment angle, ultimate strength is reduced by 27%
- Modulus remains the same



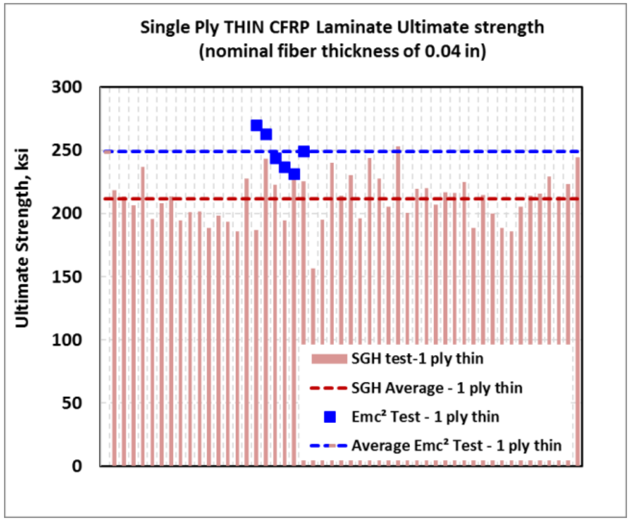


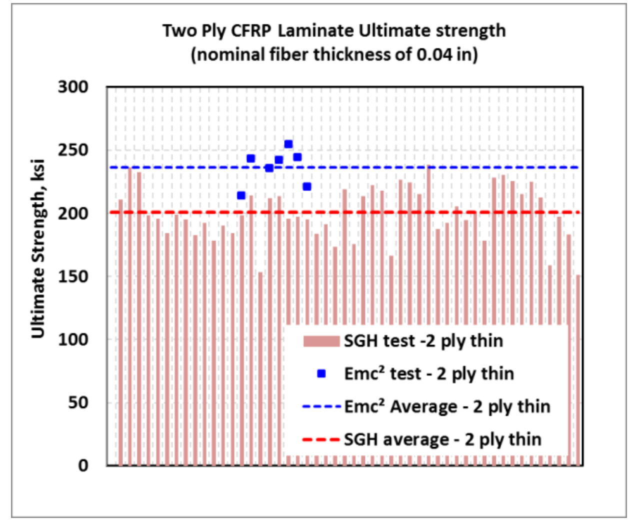
Properties	Unidirectional, width ~0.9"		Off-Axis, width ~0.86"		
	Average	COV	Average	COV	% Diff. Off-axis/Unidirectional
Ultimate Strength, ksi	236.8	3.5%	171.9	7.6%	-27.4%
Modulus, ksi	13.93	4.6%	14.23	7.7%	2.2%

Effect of Temperature on Tensile Strength

- ***CC N-871-1 recommends using tensile strength at RT for operating temperature less than 125F***
  - ***This assumes strengths are similar at RT and 125F***
  - ***Few tensile tests at 125F would give us an idea!***
- ***Tests are ongoing***

Multi-Ply Tensile Tests

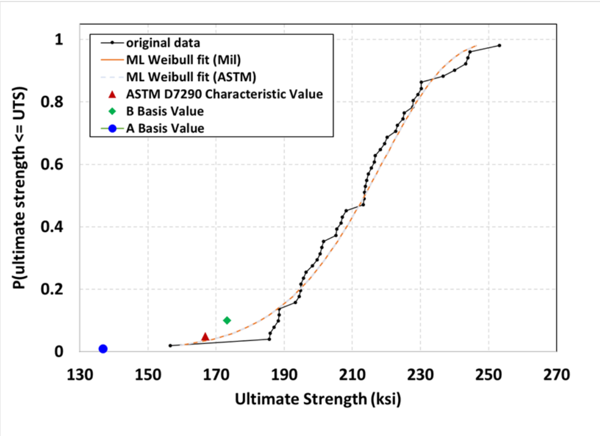


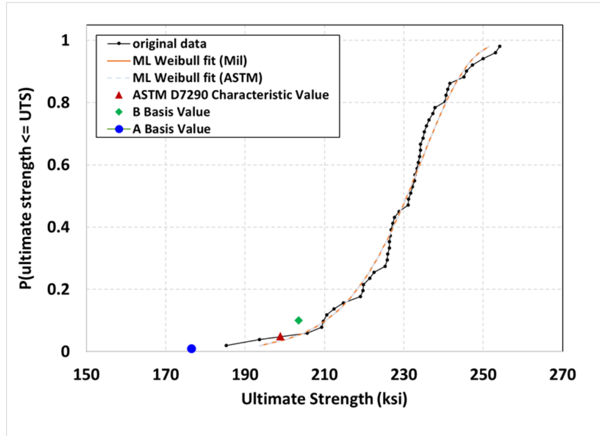


Properties	Single-ply					2-ply				
	SGH Test		Emc^2Test		% Difference	SGH Test		Emc^2Test		% Difference
	Average	COV	Average	COV	Emc^2/SGH	Average	COV	Average	COV	Emc^2/SGH
Ultimate Strength, ksi	211.5	9.0%	249.06	6.0%	17.7%	201.0	10.5%	237.81	6.4%	18.3%

- ***Average ultimate strengths for 1-ply and 2-ply tensile tests conducted at Emc^2 lab are about 18% higher than the average of 50 tests conducted at SGH***

Multi-Ply Tensile Tests - Characteristic Values of Ultimate Strength





Multi-ply strength reduction recommended in CC-N871-1

$$S_u(n) = [1-0.03(n-1)]\, S_u;$$

$S_u(n{=}2) = 0.97 S_u$; 3% reduction

$S_u(n{=}3) = 0.94 S_u$; 6% reduction

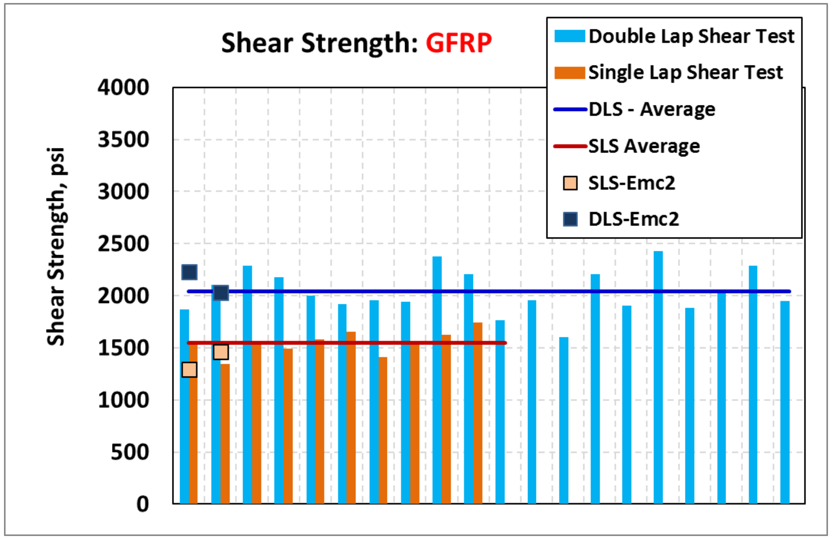
$S_u(n{=}4) = 0.91 S_u$; 9% reduction

Methods	C200HM - 1 Ply	Diff. with CC	C200HM - 2 Ply	Diff. with CC	Diff. between 1- and 2-ply
ASTM D7290 (CC N-871)	166.8		154.0		7.7%
A Basis	136.7	-18%	123.4	-20%	9.7%
B Basis	173.3	4%	160.6	4%	7.3%

- *A-basis value of ultimate strength is 18% lower than ASTM D7290 characteristic value for C200HM (thin fiber) single-ply tests (similar to thick fiber, C400HM 11% lower)*
- *For all characteristic values, 2-ply laminates showed 7-10% lower ultimate strength than 1-ply laminates*
- *In our PVP2018 paper*, we recommended using 7% reduction in ultimate strength of single-ply laminate for each additional ply*

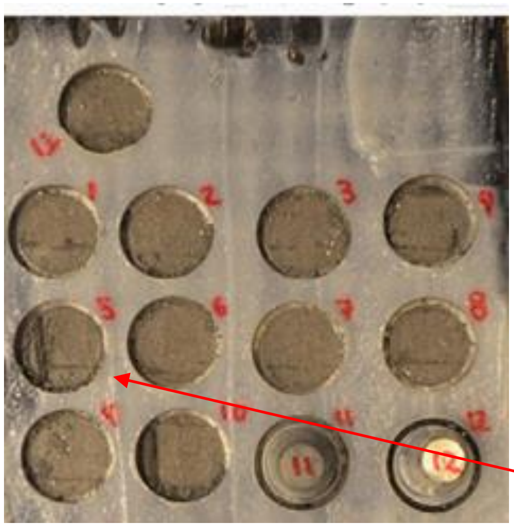
Bond Strength at Terminal Ends

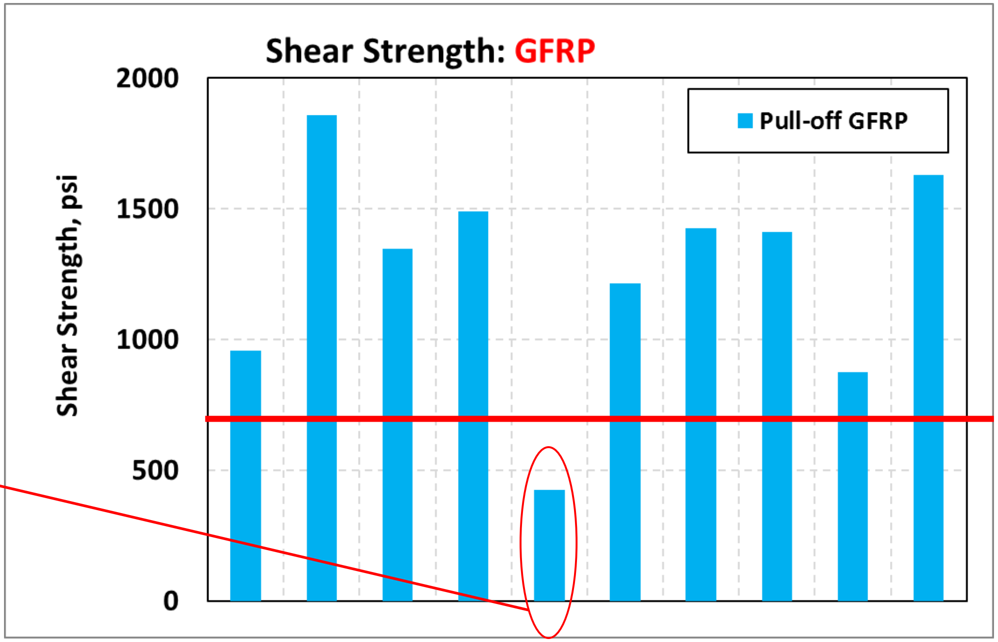
Test Method	Minimum Shear Strength, psi	Average Shear Strength, psi	COV
Double lap shear	1600.6	2043.6	10.4%
Single lap shear	1347.4	1546.1	7.5%



- *Double lap shear (DLS) and single lap shear (SLS) specimens were prepared by Structural Technologies (ST) using Glass Fiber Reinforce Plastic (GFRP) as GFRP is the first layer to bond with host steel pipe*
- *20 DLS and 10 SLS were conducted at SGH*
- *Confirmatory tensile tests were conducted at Emc^2 lab*
- *GFRP shows very similar average shear strength as SGH/ST tests for both DLS and SLS tests*
- *Minimum shear strength using both DLS and SLS specimens is greater than minimum recommended shear strength of 1,000 psi in CC N-871-1*

Pull-Off Strength at Terminal Ends





Max	1859
Min	424
Average	1263.4
St. Dev	414
Coeff. Of Var.	32.8%

- *Pull-off specimens were prepared by Structural Technologies (ST) using GFRP*
- *10 tests were conducted at SGH*
- *Average pull-off strength is greater than the minimum recommended shear strength of 700 psi in CC N-871-1.*
  - *However, one test showed pull-off strength less than 700 psi*

Durability Testing (~Mar 2020 – Dec 2021)

Material Adjustment Factors for 50 Years of Service (from Table B-1-210-1 in CC N-871-1)

Exposure Condition		Tension		Flexure		Overlap Shear and Lap Shear Strength	
		Strength C	Modulus C′	Strength C	Modulus C′	Strength C	Modulus C′
Water	73°F (23°C)	0.85	0.95	0.7	0.9	0.75	0.8
	100°F (38°C)	0.85	0.95	0.6	0.85	0.6	0.7
	140°F (60°C)	0.7	0.95	0.45	0.85	0.55	0.6
Salt Solution	73°F (23°C)	0.75	0.95	0.7	0.85	0.75	0.45
	100°F (38°C)	-	-	-	-	-	-
	140°F (60°C)						
Alkali Solution	73°F (23°C)	0.75	0.95	0.65	0.80	0.75	0.45
	100°F (38°C)	-	-	-	-	-	-
	140°F (60°C)	-	-	-	-	-	-

- ***The above material adjustment factors are available for only single-ply laminates***
- ***The current test program also includes determining material adjustment factors for single-ply and multi-ply laminates (3-layers only) at 140F under salt-solution for various loading conditions***

Variables Affecting Material Adjustment Factors

- **Temperature** –Material Adjustment Factors decrease with increase in temperature
- **Exposure environment** – Alkali and salt-water shows the most degrading effect - water shows moderate degrading effect compare to alkali and salt-water
- **Exposure Time** – Material Adjustment Factors decrease with increase in exposure time
- **Number of plies** – Material Adjustment Factors decrease with increase in number of layers
- **Loading conditions** – Material Adjustment Factors vary with loading conditions
  - Flexural loading shows the most degrading effect on strength
  - Lap shear shows the most degrading effect on modulus
  - Tensile loading shows moderate degradation of strength

Watertightness Test (~Mar 2020)

- *Watertightness test will be conducted using CFRP repair system*

- *Current plan is to test at three different temperatures*
  - *Room temperature*
  - *Low temperature (e.g. 40F)*
  - *Maximum operating temperature (~140F)*

- *Other details for test configuration: being developed*

Full-Scale Hydrostatic Test (~Aug 2020)

- ***Full-scale hydrostatic test will be conducted with CFRP repair system***
- ***Test will be conducted at room temperature***
- ***Pipe dimension: > 40 inch diameter***
- ***Detailed test configuration: still being developed***

Effective Factor of Safety

Various strength reduction phenomena	The strength reduction factors determined from tests or available literature	Time dependent factors (Y/N)
Difference in Characteristic values of ultimate strength of single-ply CFRP lamina (ASTM D7290 vs A basis)	0.82-0.89	No, needs to be accounted toward effective factor of safety
Effect of misalignment angle	0.73	
Effect of temperature, F_{temp} (RT vs 125F)	TBD	
Strength reduction in multi-ply laminates	Preliminary results on 2-ply - 0.93 TBD for 3-ply and 4-ply	
Time effect factor	0.6	Yes, can be addressed by reducing service life
Long-term material degradation factors on ultimate strength and modulus	TBD (0.45 from limited available data)	

Effective FS = 10.0 X 0.82 X 0.73 X F_{temp} X 0.91 X 0.6 X 0.45 = 1.47 << 3.5

- ***The on-going tests will help better estimating the factors in red***
- ***However, the preliminary results and the trend from available limited test data indicate lower values which will further reduce the effective FS (lower than 1.47)***

Summary

- Various single-ply tensile tests revealed that the following parameters have a diminishing effect on the ultimate strength of CFRP
  - Characteristic values - ASTM D7290 vs A basis
  - Misalignment angle
- From the preliminary results on multi-ply laminate tests, the degradation effect on multi-ply laminates seems more than what is recommended in CC-N-871-1
  - Update will be provided after completing all tests
- Bond strengths at terminal ends seem reasonably captured in CC N-871-1
- On going tests
  - Durability testing will provide an estimation of material adjustment factors for possible worst-case condition
    - Salt-solution at 140F for single-ply and multi-ply laminates
  - Watertightness test will provide effectiveness of GFRP for the range of operating temperature
  - Full-scale test will provide the validation of overall design of the repair system including fabrication, installation etc.

Acronyms

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CC	Code Case
CFRP	Carbon Fiber Reinforced Plastic
COV	Coefficient of Variance
DLS	Double Lap Shear
Emc^2	Engineering Mechanics Corporation of Columbus
GFRP	Glass Fiber Reinforced Plastic
SGH	Simpson Gumpertz & Heger
SLS	Single Lap Shear
ST	Structural Technologies