Pultrusion Conference 2021

Validation Testing of a Custom Pultruded FRP Shape for Long-span, Permanent Load Conditions

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Meet your speaker

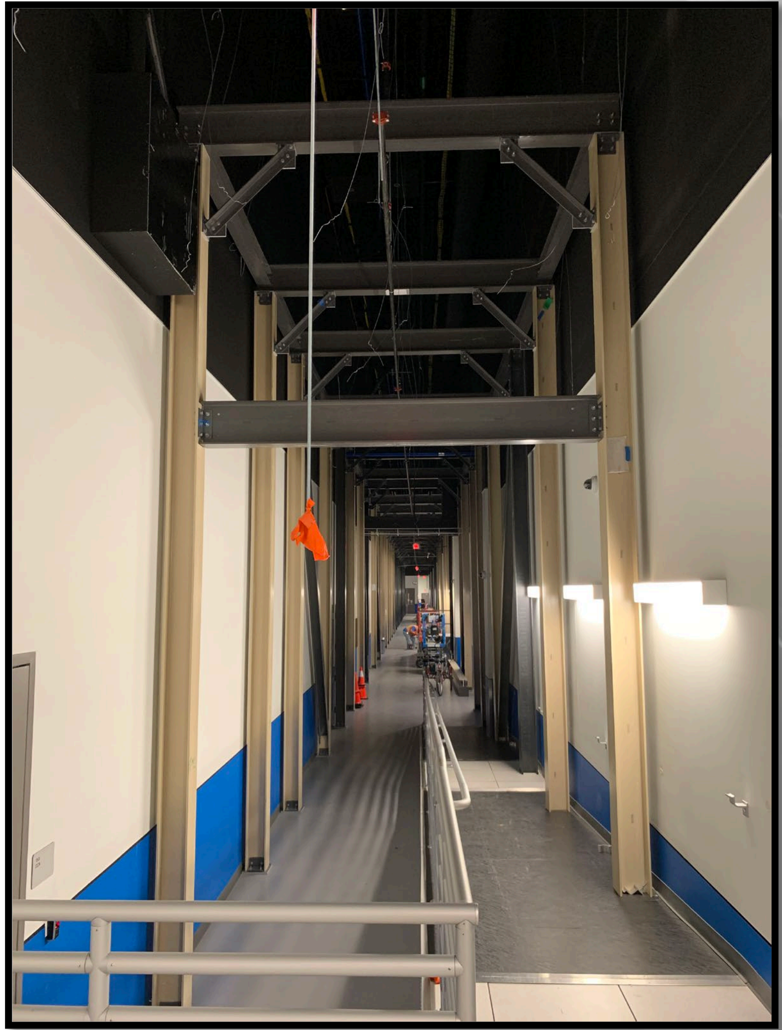
- Richard (Rich) Estes, PE
- BSCE University of Notre Dame [2013]
- Oilfield Engineer [2013-15]
- Public Works Engineer [2015-17]
- Structural Engineer [2017-current] <- Designing with FRP since 2017

Objectives

- Applications and needs for custom pultruded FRP shapes
- Case study of a validation testing program
- Statistical analysis worked example
- Lessons learned

Applications and Needs

Mission Critical



Industrial

Equipment Access and Support

FRP Industry Needs

- Seismic design
- Moment resisting connections
- Diaphragm action
- **Longer spans**

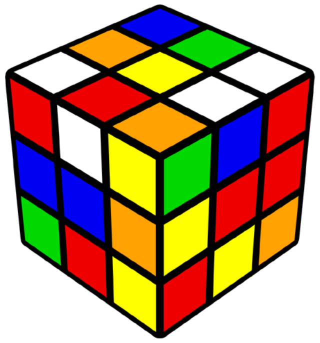
Case Study

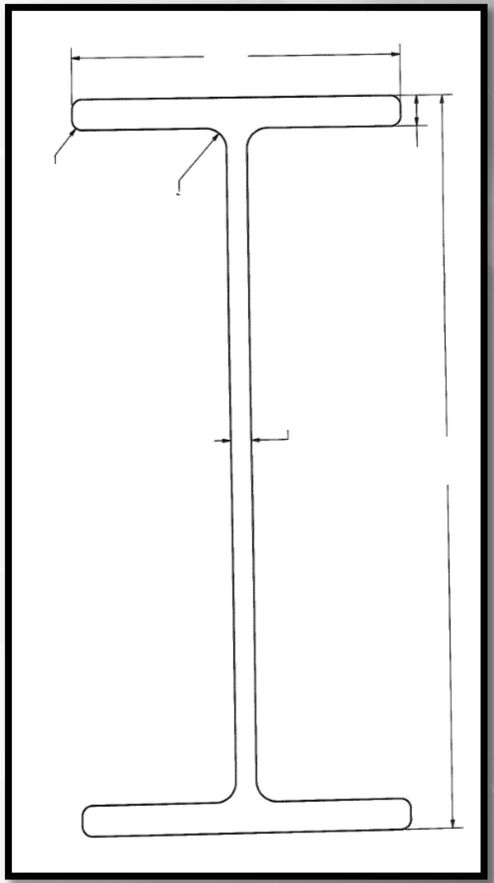
Mission Critical – Long Span Permanent Load

- Steel primary frame
- FRP infill beams
- Span $\geq$ 20 ft
- Dead load = 30-160 psf (equipment)
- Beam spacing $\geq$ 4 ft
- Deflection limit = L/240

Optimization Limits

- Optimize cross-sectional area
- Limit depth and width to 18”
- Non-uniform thickness permissible
- Maximum thickness of 1”
- Strength and deflection checked per the provisions of the LRFD Pre-Standard





Preliminary Results

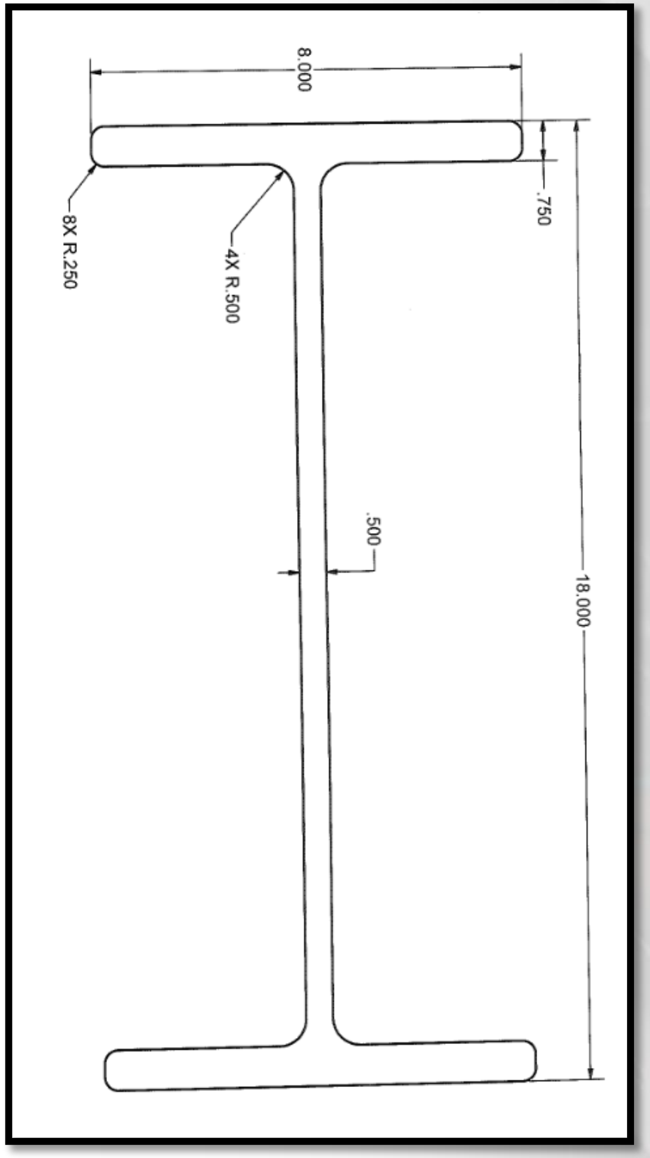
Uniform Load [psf]	Spacing [ft]	Span [ft]	Unbraced Span [ft]	Optimized Beam Size [depthxflange widthxthickness]	Beam Area [in^2]	Optimized Steel Beam [W#x#]
160	6	20	20	18x15x7/8	40.5	12x30
160	5.5	20	20	16x15x7/8	38.8	8x28
160	5	20	20	18x15x13/16	37.7	8x28
160	4.5	20	20	16x15x13/16	36.1	12x26
160	4	20	20	18x14x3/4	33.4	8x24
100	6	20	20	16x14x3/4	31.9	8x24
100	5.5	20	20	16x14x3/4	31.9	8x24
100	5	20	20	14x14x3/4	30.4	8x24
100	4.5	20	20	12x14x3/4	28.9	10x22
100	4	20	20	18x13x5/8	26.8	6x20
60	6	20	20	16x13x5/8	25.5	6x20
60	5.5	20	20	14x13x5/8	24.2	6x20
60	5	20	20	18x12x9/16	23	8x18
60	4.5	20	20	16x12x9/16	21.9	8x18
60	4	20	20	18x12x1/2	20.5	6x15
50	6	20	20	18x12x9/16	23	8x18
50	5.5	20	20	16x12x9/16	21.9	8x18
50	5	20	20	16x12x9/16	21.9	6x15
50	4.5	20	20	18x12x1/2	20.5	6x15
50	4	20	20	16x12x1/2	19.5	6x15
40	6	20	20	18x12x1/2	20.5	6x15
40	5.5	20	20	18x12x1/2	20.5	6x15
40	5	20	20	16x12x1/2	19.5	6x15
40	4.5	20	20	14x12x1/2	18.5	6x15
40	4	20	20	18x11x7/16	17.2	6x15
30	6	20	20	14x12x1/2	18.5	6x15
30	5.5	20	20	18x11x7/16	17.2	6x15
30	5	20	20	16x11x7/16	16.3	6x15
30	4.5	20	20	16x11x7/16	16.3	10x15
30	4	20	20	14x11x7/16	15.4	6x12

Uniform Load [psf]	Spacing [ft]	Span [ft]	Unbraced Span [ft]	Optimized Beam Size [depthxflange widthxthickness]	Beam Area [in^2]	Optimized Steel Beam [W#x#]
160	6	25	25	n/a		14x43
160	5.5	25	25	n/a		10x39
160	5	25	25	18x18x1	52	10x39
160	4.5	25	25	18x18x1	52	10x39
160	4	25	25	18x18x15/16	48.9	10x33
100	6	25	25	18x17x15/16	47	10x33
100	5.5	25	25	18x17x7/8	44	8x31
100	5	25	25	16x17x7/8	42.2	8x31
100	4.5	25	25	18x17x13/16	40.9	8x31
100	4	25	25	16x16x13/16	37.7	8x28
60	6	25	25	18x16x3/4	36.4	8x28
60	5.5	25	25	16x16x3/4	34.9	8x24
60	5	25	25	18x15x11/16	32.1	8x24
60	4.5	25	25	16x15x11/16	30.7	8x24
60	4	25	25	16x15x11/16	30.7	8x24
50	6	25	25	18x15x11/16	32.1	8x24
50	5.5	25	25	18x15x11/16	32.1	8x24
50	5	25	25	16x15x11/16	30.7	8x24
50	4.5	25	25	18x15x5/8	29.2	8x24
50	4	25	25	16x15x5/8	27.9	6x20
40	6	25	25	16x15x11/16	30.7	8x24
40	5.5	25	25	18x15x5/8	29.2	10x22
40	5	25	25	16x15x5/8	27.9	6x20
40	4.5	25	25	18x14x9/16	25.3	6x20
40	4	25	25	18x14x9/16	25.3	6x20
30	6	25	25	18x14x9/16	25.3	6x20
30	5.5	25	25	18x14x9/16	25.3	6x20
30	5	25	25	16x14x9/16	24.2	6x20
30	4.5	25	25	18x13x1/2	21.5	8x18
30	4	25	25	18x13x1/2	21.5	6x15

Uniform Load [psf]	Spacing [ft]	Span [ft]	Unbraced Span [ft]	Optimized Beam Size [depthxflange widthxthickness]	Beam Area [in^2]	Optimized Steel Beam [W#x#]
160	6	20	10	18x10x3/4	27.4	14x22
160	5.5	20	10	18x10x3/4	27.4	14x22
160	5	20	10	16x10x3/4	25.9	12x22
160	4.5	20	10	14x10x3/4	24.4	8x21
160	4	20	10	16x10x11/16	23.8	8x18
100	6	20	10	12x10x3/4	22.9	8x18
100	5.5	20	10	18x9x5/8	21.7	8x18
100	5	20	10	16x9x5/8	20.5	10x17
100	4.5	20	10	14x9x5/8	19.2	10x17
100	4	20	10	12x9x5/8	18	8x15
60	6	20	10	12x9x5/8	18	10x15
60	5.5	20	10	14x9x9/16	17.4	12x14
60	5	20	10	18x8x1/2	16.5	8x13
60	4.5	20	10	16x8x1/2	15.5	8x13
60	4	20	10	18x8x7/16	14.5	10x12
50	6	20	10	18x8x1/2	16.5	8x13
50	5.5	20	10	16x8x1/2	15.5	8x13
50	5	20	10	14x8x1/2	14.5	10x12
50	4.5	20	10	18x8x7/16	14.5	10x12
50	4	20	10	16x8x7/16	13.5	8x10
40	6	20	10	18x8x7/16	14.5	10x12
40	5.5	20	10	12x8x1/2	13.5	10x12
40	5	20	10	16x8x7/16	13.5	8x10
40	4.5	20	10	14x8x7/16	12.74	8x10
40	4	20	10	18x7x3/8	11.72	6x9
30	6	20	10	14x8x7/16	12.74	8x10
30	5.5	20	10	14x8x7/16	12.74	8x10
30	5	20	10	18x7x3/8	11.72	6x9
30	4.5	20	10	16x7x3/8	10.97	6x8.5
30	4	20	10	14x7x3/8	10.22	6x8.5

Load Criteria Refinement

- Dead load = 60 psf
- Beam spacing = 5 ft
- Span = 24 ft
- Unbraced span = 8 ft
- Final shape = 18 x ½ x 8 x ¾



Why Test?

- Outperform the code prescribed capacity equations
- Establish performance confidence

Test Rig

Load Cell

Actuator

Top Flange Lateral Bracing

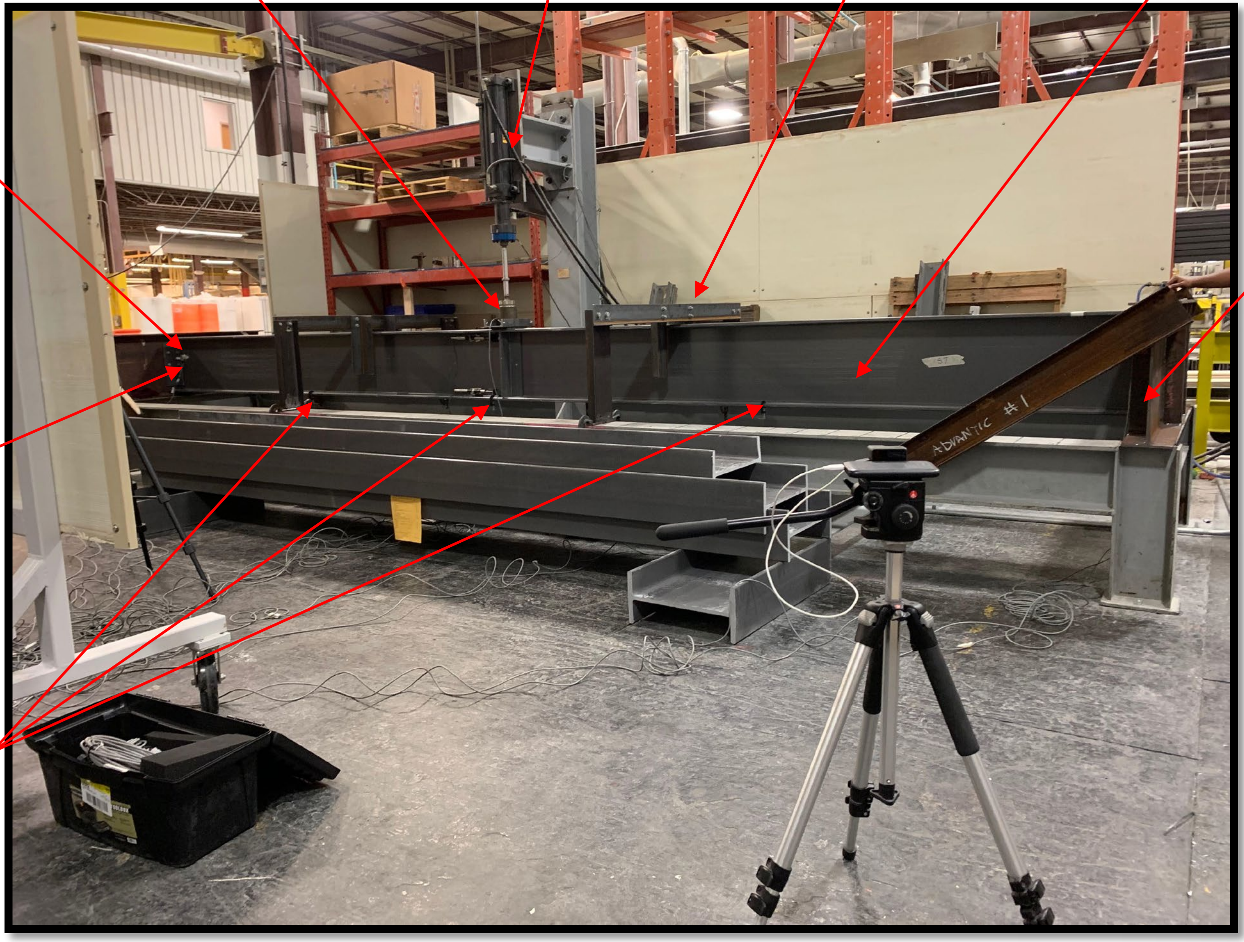
FRP Beam

Clinometers

Steel Support Frame

FRP Shear Clips (x2) with 1/2" dia. A325 bolts

String Potentiometers

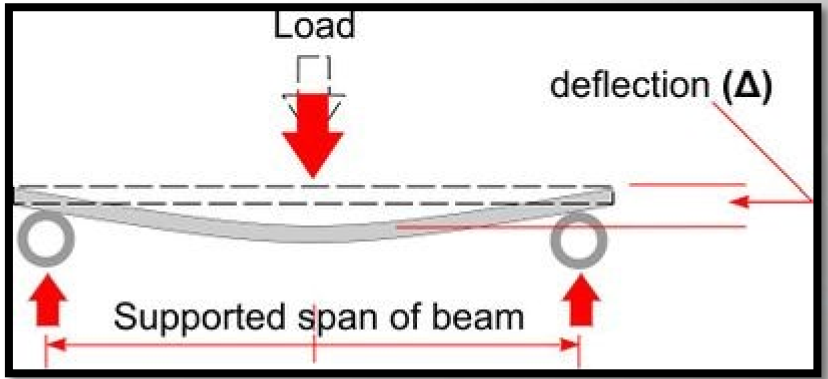


Test Video

Initial Top of
Beam Elevation

Test Results

- Apparent stiffness, $EI = 3.4x10^6$ k-in^2
- Deflection, Δ:
  - Before testing, predicted $\Delta = 0.87''$
  - After testing, $\Delta = 0.7''$



http://wiki.dtonline.org/index.php/Beam_Deflection

Statistics Worked Example

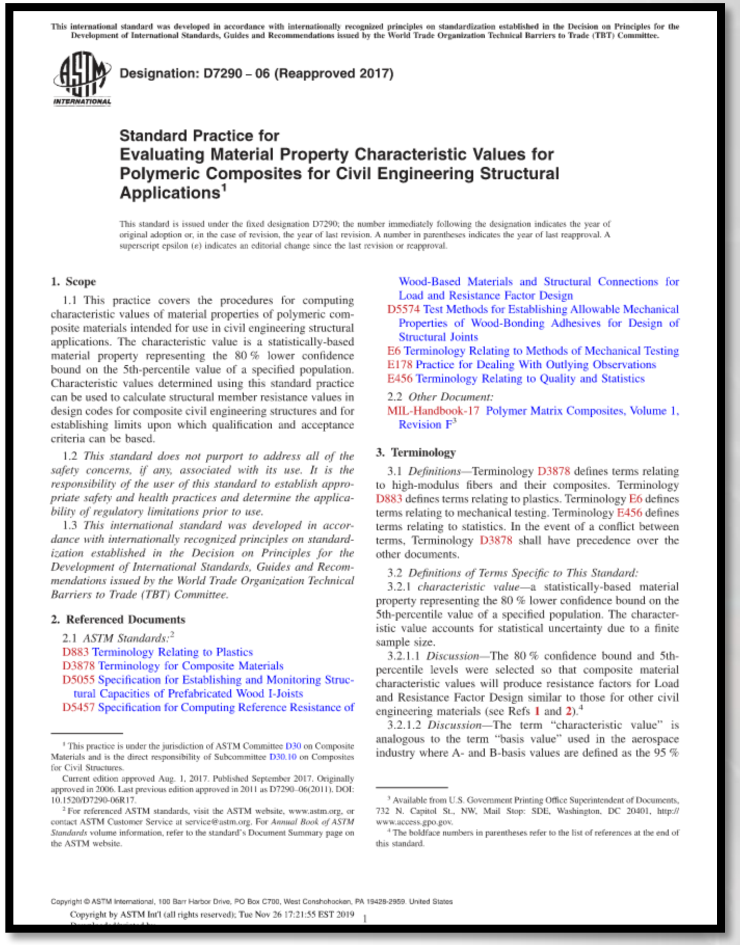
Referenced Standards

Pre-Standard for
Load & Resistance Factor
Design (LRFD) of Pultruded
Fiber Reinforced Polymer (FRP)
Structures
(Final)

Submitted to:
American Composites Manufacturers
Association (ACMA)

November 9, 2010

ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS



This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: D7290 – 06 (Reapproved 2017)

Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications[1]

This standard is issued under the fixed designation D7290; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the procedures for computing characteristic values of material properties of polymeric composite materials intended for use in civil engineering structural applications. The characteristic value is a statistically-based material property representing the 80 % lower confidence bound on the 5th-percentile value of a specified population. Characteristic values determined using this standard practice can be used to calculate structural member resistance values in design codes for composite civil engineering structures and for establishing limits upon which qualification and acceptance criteria can be based.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D883 Terminology Relating to Plastics
D3878 Terminology for Composite Materials
D5055 Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists
D5457 Specification for Computing Reference Resistance of Wood-Based Materials and Structural Connections for Load and Resistance Factor Design
D5574 Test Methods for Establishing Allowable Mechanical Properties of Wood-Bonding Adhesives for Design of Structural Joints
E6 Terminology Relating to Methods of Mechanical Testing
E178 Practice for Dealing With Outlying Observations
E456 Terminology Relating to Quality and Statistics

2.2 *Other Document:*

MIL-Handbook-17 Polymer Matrix Composites, Volume 1, Revision F[3]

3. Terminology

3.1 *Definitions*—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. Terminology E456 defines terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other documents.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *characteristic value*—a statistically-based material property representing the 80 % lower confidence bound on the 5th-percentile value of a specified population. The characteristic value accounts for statistical uncertainty due to a finite sample size.

3.2.1.1 *Discussion*—The 80 % confidence bound and 5th-percentile levels were selected so that composite material characteristic values will produce resistance factors for Load and Resistance Factor Design similar to those for other civil engineering materials (see Refs **1** and **2**).[4]

3.2.1.2 *Discussion*—The term "characteristic value" is analogous to the term "basis value" used in the aerospace industry where A- and B-basis values are defined as the 95 %

[1] This practice is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

Current edition approved Aug. 1, 2017. Published September 2017. Originally approved in 2006. Last previous edition approved in 2011 as D7290–06(2011). DOI: 10.1520/D7290-06R17.

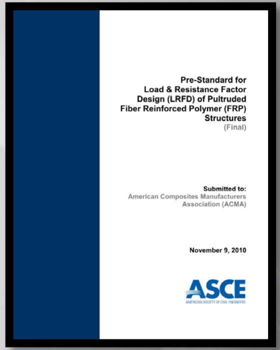
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from U.S. Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401, http://www.access.gpo.gov.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

1

Pre-Standard Section 2.4.3


Pre-Standard for
Load & Resistance Factor
Design (LRFD) of Pultruded
Fiber Reinforced Polymer (FRP)
Structures
(Final)

Submitted to:
American Composites Manufacturers
Association (ACMA)

November 9, 2010

ASCE

2.4.3 Statistical Basis for Reference Strength and Stiffness

The reference strength and stiffness shall be determined in accordance with ASTM D7290. A minimum of 10 samples shall be tested to determine the reference strength or stiffness.

(a) Reference strength. The strength of pultruded FRP composite structural members and components shall be assumed to be described by a two-parameter Weibull distribution. The reference strength shall equal the characteristic value, defined at the 80% lower confidence interval on the 5th-percentile of the Weibull distribution.

(b) Reference stiffness. The elastic modulus in the longitudinal direction and in-plane shear modulus shall be described by two-parameter Weibull distributions.

(1) Strength and stability. The reference stiffness shall equal the characteristic value of the governing Weibull distribution.

(2) Structural analysis. The reference stiffness shall equal the mean value of the governing Weibull distribution.

ASTM D7290


Designation: D7290 – 06 (Reapproved 2017)

Standard Practice for
Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications[1]

1. Scope

1.1 This practice covers the procedures for computing characteristic values of material properties of polymeric composite materials intended for use in civil engineering structural applications. The characteristic value is a statistically-based material property representing the 80 % lower confidence bound on the 5th-percentile value of a specified population. Characteristic values determined using this standard practice can be used to calculate structural member resistance values in design codes for composite civil engineering structures and for establishing limits upon which qualification and acceptance criteria can be based.

Wood-Based Materials and Structural Connections for Load and Resistance Factor Design
D5574 Test Methods for Establishing Allowable Mechanical Properties of Wood-Bonding Adhesives for Design of Structural Joints
E6 Terminology Relating to Methods of Mechanical Testing
E178 Practice for Dealing With Outlying Observations
E456 Terminology Relating to Quality and Statistics

2.2 Other Document:
MIL-Handbook-17 Polymer Matrix Composites, Volume 1, Revision F

1. Mean and standard deviation
2. Outlying observations
3. Material property value probability distribution
4. Maximum likelihood parameter estimates and coefficient of variation
5. Nominal value (two-parameter Weibull distribution)
6. **<u>Characteristic value (80% confidence bound, 5th-percentile value)</u>**


Designation: D7290 – 06 (Reapproved 2017)

Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications

1. Calculate the Mean and Standard Deviation

- Sample mean, $\bar{x} = 4{,}051{,}870\ k - in^2$
- Sample standard deviation, $s_{n-1} = 252{,}524\ k - in^2$

2. Detection of Outlying Observations

- Outliers can skew the results
- Additional investigation may be required

3. Assumed Material Property Distribution

- $f(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\beta-1} exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$

4a. Maximum Likelihood Parameter Estimation


Designation: D7290 − 06 (Reapproved 2017)

Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications

- $$\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}} ln(x_i)}{\sum_{i=1}^{n} x_i^{\hat{\beta}}} - \frac{1}{\hat{\beta}} - \frac{1}{n}\sum_{i=1}^{n} ln(x_i) = 0$$
  - Adjust $\hat{\beta}$ until equation is solved, $\hat{\beta}$ = 22.5
- $$\hat{\alpha} = \left(\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}}}{n}\right)^{\frac{1}{\hat{\beta}}} = 4{,}150{,}373$$


Designation: D7290 – 06 (Reapproved 2017)

Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications

4b. Coefficient of Variation

- $COV = \frac{\sqrt{\Gamma\left(1+\frac{2}{\hat{\beta}}\right)-\Gamma^2\left(1+\frac{1}{\hat{\beta}}\right)}}{\Gamma\left(1+\frac{1}{\hat{\beta}}\right)} = 0.055$

5. Nominal Value

- $x_{0.05} = \hat{\alpha} * [0.0513]^{\frac{1}{\hat{\beta}}} = 3{,}637{,}132\ k - in^2$

6. Characteristic Value

D7290 – 06 (2017)

TABLE 1 Data Confidence Factor, Ω, on the 5th-Percentile Value for a Weibull Distribution with 80 % Confidence[A] (Refs 3 and 4)

n	COV 0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50
10	0.950	0.899	0.849	0.800	0.752	0.706	0.619	0.541
11	0.953	0.906	0.860	0.814	0.769	0.725	0.642	0.567
12	0.956	0.913	0.869	0.826	0.783	0.741	0.662	0.589
13	0.959	0.918	0.876	0.835	0.795	0.755	0.679	0.609
14	0.961	0.922	0.883	0.844	0.805	0.767	0.694	0.626
15	0.963	0.926	0.889	0.851	0.814	0.778	0.707	0.641
16	0.965	0.929	0.894	0.858	0.822	0.787	0.719	0.655
18	0.968	0.935	0.902	0.869	0.836	0.803	0.739	0.678
20	0.970	0.940	0.909	0.878	0.847	0.816	0.755	0.698
22	0.972	0.944	0.914	0.885	0.856	0.827	0.769	0.714
24	0.974	0.947	0.919	0.891	0.864	0.836	0.781	0.728
26	0.975	0.949	0.923	0.897	0.870	0.844	0.791	0.741
28	0.976	0.952	0.927	0.902	0.876	0.851	0.800	0.752
30	0.977	0.954	0.930	0.906	0.882	0.857	0.809	0.761
32	0.978	0.956	0.933	0.910	0.886	0.863	0.816	0.770
34	0.979	0.957	0.935	0.913	0.890	0.868	0.822	0.778
36	0.980	0.959	0.938	0.916	0.894	0.872	0.828	0.785
38	0.980	0.960	0.940	0.919	0.897	0.876	0.833	0.791
40	0.981	0.962	0.942	0.921	0.901	0.880	0.838	0.797
42	0.982	0.963	0.943	0.924	0.904	0.883	0.843	0.803
44	0.982	0.964	0.945	0.926	0.906	0.886	0.847	0.808
46	0.983	0.965	0.946	0.928	0.909	0.889	0.851	0.813
48	0.983	0.966	0.948	0.929	0.911	0.892	0.854	0.817
50 or more	0.984	0.967	0.949	0.931	0.913	0.895	0.858	0.821

[A] Linear interpolation is permitted. For *COV* values below 0.05 ($\hat{\beta}$ > 24.95), the values for *COV* = 0.05 shall be used.

- $x_{char} = \Omega * x_{0.05} = 3{,}418{,}904\ k - in^2$

Lessons Learned

Testing

- Need a significant testing apparatus in size and strength
- Adjustable support frame for varying beam lengths
- More tests increase confidence leading to a better performance

Installation

- Steel erection crew not required
- 4-5 person install crew
- Experienced install time of 10 minutes per beam
- Equivalent steel beam = W14x30 (no lateral bracing)
- Significant shipping cost reduction due to the lesser weight of the infill beams
- Savings of approximately 5% of the total structure weight
- Easy to maneuver within the existing space
- Ability to match drill bracing connections in the field

Questions?

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