

Development of a Design Standard for Pultruded Fiber Reinforced Polymer Structures

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(Lawrence C. Bank, The City College of New York)



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40 m Fiberline footbridge in Kolding, Denmark

12 standard shapes



Range of steel bolts

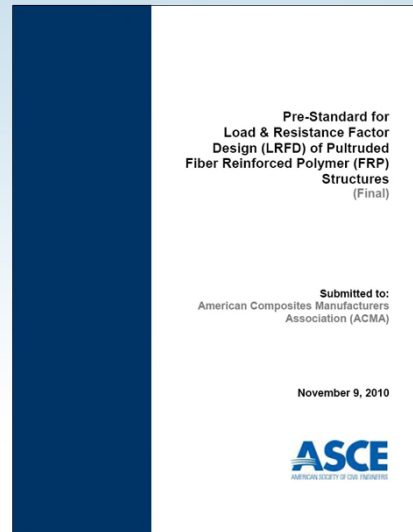


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LRFD

- **Engineering design method where the structural safety is controlled by:**
 - **Load Factors;**
material independent
 - **Resistance Factors (Φ);** material and failure mode specific



LRFD – Resistance Factors (Φ)

- **Decreases critical load needed to reach a given failure mode**
- **May differ depending on the loading condition; shear, bending, etc.**
- **Determined using statistical methods based on the desired reliability index and variance in the nominal strength**



LRFD – Resistance Factors (ϕ)

- Due to the lack of experimental data in pultruded FRP structures a conservative approach was taken with the reliability index
 - To calculate ϕ factors the material properties of the members being tested must be directly measured in addition to any failure loads

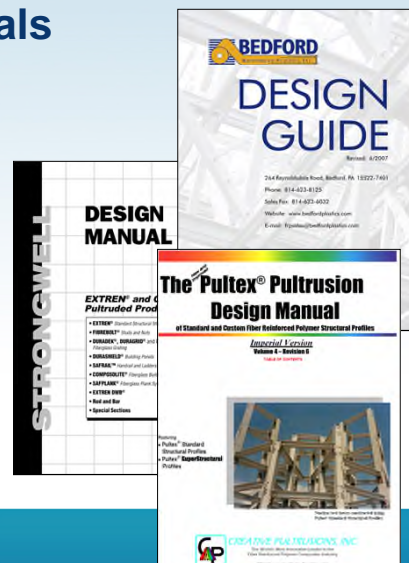


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Current American Practice

- Pultruder Design Manuals
 - Allowable stress design
 - Online
 - Provide section sizes & material properties
 - Provide equations for controlling limit states
 - Provide lookup tables and design aids



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Standard Development

- **Chapters were developed which:**
 - **Contained the scope, provisions and requirements needed to apply the pre-standard (Chapters 1-2)**
 - **Governed the design of all structural stress states; compression, tension, bending, shear, connections, etc. (Chapters 3-8)**



Standard Development

- **For each design chapter (3-8)**
 - **All known failure modes were identified**
 - **Design equations were proposed**
 - **Literature review was conducted**
 - **Professional factors were calculated**
 - **Compared published experimental data with an equation to determine its accuracy**
 - **Required to help develop resistance factors**



Standard Development

- **Chapters contained only mandatory provisions which must be followed**
- **Commentary contained**
 - Reference sources to the equations
 - Further explanation of the mandatory text
 - Additional non-mandatory design recommendations



Chapter Overviews

- **Ch. 1 GENERAL PROVISIONS**
 - Scope, referenced specs. and codes
 - Material definition – minimum properties
 - Design Basis – LRFD defined
 - Load Combinations
 - Other fabrication, construction and quality requirements



Chapter 1

- **Outlines LRFD design basis which applies to entire standard**
- **Defines all requirements for material constituent components**
 - **Fiber type, orientations, volume fraction**
 - **Resin type**
 - **Pultruded material minimum strengths**



Chapter 1 – Material Properties

- **A uniform method of calculating and publishing material properties was adopted in the pre-standard**



Designation: D 7290 – 06

**Standard Practice for
Evaluating Material Property Characteristic Values for
Polymeric Composites for Civil Engineering Structural
Applications¹**



Chapter 1 – Material Properties

- Allows for any user of the Standard to be confident in any manufacturer's reported properties for design
- Characteristic value must be reported as
 - 80% lower confidence bound on the 5th percentile value, minimum of 10 samples per batch
 - Used to calculate Φ factors in the Standard



Chapter 1 – Material Properties

Table 1.3-2(a) Minimum Required Characteristic Mechanical Properties for FRP Composite Shapes

Mechanical Property	Minimum Requirement	ASTM Test Method	Minimum Number of Tests
Longitudinal Tensile Strength	30,000 psi	D638	10
Transverse Tensile Strength	7,000 psi	D638	10
Longitudinal Tensile Modulus	3×10^6 psi	D638	10
Transverse Tensile Modulus	0.8×10^6 psi	D638	10
Longitudinal Compressive Strength	30,000 psi	D6641	10
Longitudinal Compressive Modulus	3×10^6 psi	D6641	10
Transverse Compressive Modulus	1×10^6 psi	D6641	10
In-Plane Shear Strength	8,000 psi	D5379	10
In-Plane Shear Modulus	0.4×10^6 psi	D5379	10
Interlaminar shear strength	3,500 psi	D2344	10
Longitudinal pin-bearing strength	21,000 psi	D953 ^a	10
Transverse pin-bearing strength	18,000 psi	D953 ^a	10



Chapter Overviews

- **Ch. 2 DESIGN REQUIREMENTS**
 - Design and nominal strength definition
 - Stability requirements
 - Serviceability requirements
 - Ponding, fatigue and connection requirements



Chapter 2 - Serviceability

- Shear deformation must be considered for members with a span-depth ratio < 20
- Specifies E and G values that can be used for deflection calculations
- Adjustment for long-term loading
- Applies to all chapters and will often control design



Chapter 2

- Bracing requirements defined
- Testing is allowed for the design of elements not covered by the Standard
- Design strength reduction factors for time effects, resistance factors, moisture and temperature conditions defined



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Chapter 2 – Time Effects

$$R_u \leq \lambda \phi R_n$$

Load Combination (1.5.2(a))	Time Effect Factor (λ)
1.4D (permanent load)	0.4
1.2D + 1.6L + 0.5(L _r or S or R)	0.8 when L is from occupancy 0.6 when L is from storage 1.0 when L is from impact
1.2D + 1.6(L _r or S or R) + (0.5L or 0.5W)	0.75
1.2D + 1.0W + 0.5L + 0.5(L _r or S or R)	1.0
1.2D + 1.0E + 0.5L + 0.2S	1.0
0.9D + 1.0W	1.0
0.9D + 1.0E	1.0
1.5.2(b) – Flood loads	0.75
1.5.2(c) – Atmospheric ice loads	0.75

R_u is Design strength; R_n is Nominal strength; ϕ is Resistance factor



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Chapter 2

- **Knockdown factors for Nominal strength**
 - $R_n = R_0 C_M C_T C_{CH} C_{LS} C_{CA}$
 - R_0 Reference Strength
 - C_M Moisture: 0.85 → 0.95
 - C_T Temperature (°F): 0.58 → 1.0 (90 < T ≤ 140)
 - C_{CH} Chemical Environment: From ASTM C581
 - C_{LS} Loading Sharing: 1.0 → 1.2 if applicable
 - C_{CA} Composite Action: 1.0 → 1.2 if applicable



Chapter Overviews

- **Ch. 3 TENSION MEMBERS**
 - Axial tensile rupture provisions
 - Built-up member and slenderness requirements



Chapter Overviews

- **Ch. 4 COMPRESSION MEMBERS**
 - Slenderness requirements
 - Material rupture
 - Strong and weak axis global buckling
 - Flange and web local compression buckling
 - Applies to I, T, equal leg angle and hollow and solid square and circular sections



Chapter 4

- **Simple Euler buckling equation used for global buckling**
- **Web-Flange junction modeled as simply supported for local buckling**

$$F_{crx} = \frac{\pi^2 E_L}{\left(\frac{K_x L_x}{r_x} \right)^2}$$

$$F_{crf} = \frac{G_{LT}}{\left(\frac{b_f}{2t_f} \right)^2}$$



Chapter 4

- Global buckling was determined to be a critical governing failure mode

- $\Phi_{\text{global comp buckling}} = 0.70$

$$\gamma_M \cong 1.45$$



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Chapter 4

- Local flange compression buckling was determined to be a critical governing failure mode

- $\Phi_{\text{local flange comp buckling}} = 0.80$

$$\gamma_M \cong 1.25$$



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Bedford Design Guide

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Chapter Overviews

- **Ch. 5 FLEXURE AND SHEAR**
 - Flexural and Shear rupture
 - Flange and web local flexural buckling
 - Lateral-torsional buckling
 - Web shear buckling
 - Web crippling
 - Applies to I, T, Channel and Box sections



Chapter 5

- **Local web crippling is a function of**
 - Web dimensions
 - Interlaminar shear strength near the web-flange junction
 - Optional reinforcing plate size

$$R_n = 0.7ht_w F_{sh,int} \left(1 + \frac{2k + 6t_{plate} + b_{plate}}{d_w} \right)$$



Chapter 5

- **Local web crippling was identified as a critical governing failure mode**

- $\Phi_{\text{local web crippling}} = 0.70$

$$\gamma_M \cong 1.45$$



PhD Borowicz, 2010



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Chapter Overviews

- **Ch. 6 COMBINED FORCES & TORSION**
 - Members in torsion
 - Combined flexural and axial loads
 - Combined flexural, axial and torsion loads



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Chapter Overviews

- **Ch. 7 BUILT-UP MEMBERS**
 - Design of plates for
 - In-plane loading
 - Transverse loading
 - Stability
 - Built-up member guidelines
 - Panel-based assemblies
 - Light frame floors, walls and roofs



Chapter Overviews

- **Ch. 8 BOLTED CONNECTIONS**
 - Specification for bolting and connection geometry
 - Bolt strength
 - Pin-bearing strength
 - Net-tension strength
 - Shear-out strength

Does not scope adhesively bonded connections



Chapter 8

- Only applies to bearing connections
- FRP bolts & adhesive bonding not allowed
- Connecting elements must be steel or aluminum
 - Gussets, splice plates, angles
- Maximum allowed is 3 bolts in a line



Chapter 8

- Pin-bearing strength per bolt
 - Depends on angle of bearing force with respect to connecting FRP material

$$R_{br} = t d F_{\theta}^{br}$$

$$F_{\theta}^{br} = F_L^{br} \text{ when } \theta \text{ is } \leq 5^{\circ}, \text{ and, } = F_T^{br} \text{ when } \theta \text{ is } > 5^{\circ} \text{ to } 90^{\circ}$$

t is FRP thickness; d is diameter of smooth bolt; br is pin-bearing strength; L is Longitudinal; T is Transverse

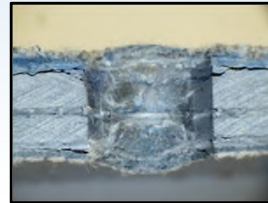
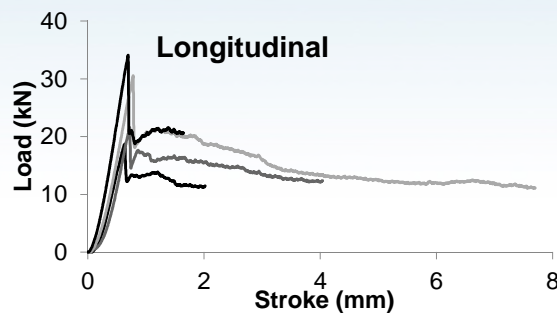


Chapter 8

- Pin-bearing strength was identified as a critical governing failure mode

- $\phi_{\text{pin bearing}} = 0.80$

$$\gamma_M \cong 1.25$$



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Chapter 8

- Net-tension strength

- One row of bolts

$$R_{nt} = \frac{1}{K_{nt,L}} (w - n d_n) t F_L^t$$

- Two or three rows of bolts*

$$R_{nt,f} = \left[\left(K_{nt,L} L_{br} \left(\frac{w}{nd} \right) \right) + \left(\frac{K_{op,L} (1 - L_{br})}{\left(1 - n \left(\frac{d_n}{w} \right) \right)} \right) \right]^{-1} w t F_L^t$$

Simplified in standard to

$$\cong 0.2 w t F_L^t$$

* J. T. Mottram, 'Prediction of net-tension strength for multi-row bolted connections of pultruded material using the Hart-Smith semi-empirical modeling approach,' *Journal of Composites for Construction*, 14 1, (2010), 105-114.

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Chapter 8

- Net-tension strength was identified as a critical governing failure mode

- $\phi_{\text{net-tension 1 row}} = 0.50$

$$\gamma_M \cong 2.0$$

- $\phi_{\text{net-tension multi rows}} = 0.45$

$$\gamma_M \cong 2.2$$



Turvey 2002



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Future Considerations

- *Code of Standard Practice for Fabrication and Installation of Pultruded FRP Structures*
 - A supplement that gives best practice designs that engineers can reference
 - Topics covered include fabrication, installation, connections, quality control...
 - Will especially aid engineers less familiar with the pultrusion industry



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Future Considerations

- Provisions for seismic design – **Chapt. 9**
- Design tables and software
- Connections
 - All FRP connections
 - Semi-rigid connection design
 - Bonded structural connections
- Full structure, frame scale, testing



Reviewing and Balloting

- PT – Project Team
 - Internal review process among different chapter authors
- PIC – Pultrusion Industry Council (ACMA)
 - Provided feedback from pultrusion industry perspective



Reviewing and Balloting

- **PAC – Project Advisory Committee**
 - Provided guidance towards meeting all ASCE standard requirements
- **Trial Designs – Engineering Firms**
 - Helped gage usability of pre-standard
- **Fiber Composite and Polymer Standards (FCAPS) Committee**
 - ASCE Standard Committee
 - Accredited by the American National Standards Institute (ANSI)
 - 27 Ballots as of August 2014



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Future Implications

- **Standard is a legal document if referenced by statute in the local building code.**
- **Easier to market pultruded structures**
- **Competes better with conventional structural materials**



www.Strongwell.com



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Future Implications

- Makes industry adopt one property data reporting method
- Will produce reliable, repeatable designs
- Tool to help educate those unfamiliar with pultrusion



Creative Design Guide



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UK and European Projects

- '*Guidance for the Design of FRP Bridges*' ad hoc group with NGCC, UK.
- '*Fiber Reinforced Polymer Structures,*' Scientific and Technical Report, WG4 of CEN/TC 250 for EN structural design codes (Eurocodes).
- '*Revised CUR96 FRP Composite Structures,*' The Netherlands.

Unknown publication dates



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Thank You

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