New Standard for LRFD Design of Pultruded Structures

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Outline

- Background
- Section 1- LRFD Design Philosophy
- Section 2 – Material Requirements
- Section 3 – Design of Members
- Section 4 – Design of Connections
- Section 5 - Seismic Design
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Background

ASCE/SEI 74 - LRFD DESIGN OF PULTRUDED FRP STRUCTURES

ASCE Standard – ASCE/SEI 74–xx

- This standard was developed by a consensus standards development process that has been accredited by the American National Standards Institute (ANSI).
- Accreditation by ANSI signifies that the standards development process used by ASCE has met the ANSI requirements for
  - openness,
  - balance,
  - consensus, and
  - due process.

ASCE·STANDARD → ASCE/SEI¶

74-XX¶

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Load·and·Resistance·Factor·Design·(LRFD)·for·Pultruded·Fiber·Reinforced·Polymer·(FRP)·Structures¶

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI STRUCTURAL ENGINEERING INSTITUTE

Section Break (Continuous)

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Why A Design Standard is Needed

- The Standard
  - follows the **consensus process of ASCE** which is open to all members of Fiber Composites and Polymers Standards (FCAPS) committee of ASCE and to the public.
  - follows the **consensus process**, which is documented, reviewed and approved by the American National Standard Institute (ANSI).
  - provides a set of **mandatory requirements** for the design of pultruded FRP structure.
  - provides a **basis for standard of care for design** of such structures in legal jurisdictions.
  - **drastically reduces the risks** associated with the design of pultruded FRP structures for a structural designer who has followed the standard before the structure can be constructed.

Design Challenges Pultruded FRP Composites

- **Anisotropic/Orthotropic** and more difficult to design, but allow innovation
- **Creep and creep rupture** which must be accounted for in design
- **Long-term exposure to certain environments** which must be accounted for in design when we expect the end-use properties differ from the initial properties

Photo of Cooling Tower Courtesy of Creative Composites Group

Design Applications Goal of Standard

- **New buildings** and other structures constructed of pultruded glass fiber reinforced polymer (FRP) composite structural shapes and profiles
- **Connection design**
- **Prefabricated** building components
- **Industrial structures** that are exposed to adverse environments as pultruded FRP is resistant to corrosive environments such as sea water.
- **Structures to withstand earthquake** as pultruded FRP has very high strength-to-weight ratio.

Photo Courtesy of Creative Composites Group

The Standard Table of Contents

- The Standard consists of **nine chapters** of **Mandatory** provisions along with nine chapters of **Commentary**.
- **Chapters:**
    1. General Provisions
    2. Design Requirements
    3. Design of Tension Members
    4. Design of Compression Members
    5. Design of Members for Flexure and Shear
    6. Design of Members Subject to Combined Forces and Torsion
    7. Design of Plates and Built-up Members
    8. Design of Bolted Connections
    9. Seismic Design Requirements
    10. Glossary
    11. Symbols

Section 1

LRFD Design Philosophy

LRFD Design Objective

- Designs made in conformance to the requirements of ASCE/SEI 74 shall meet the following
  - Strength – Determined from the results of short-term tests resistance performed on new materials.
  - Time Effects – Accounts for the creep and creep rupture of the material under sustained load for the duration of design life of the structure.
  - Durability – Accounts for design properties such as strength and modulus in the end-use condition. It is obtained testing the retained properties after exposure to the expected environment for the duration of design life.
  - Reliability – Account for the effect of variability of load and variability of resistance as they affect the reliability of the structure, i.e. the probability of failure, is in par with all other materials of construction.

Basic Requirement

Design is based on the following:

$$R_u \leqq \lambda \phi R_n = \lambda \phi (C R_o)$$

R_u = required strength when structure is subjected to factored load combinations

λ = time effect factor, accounts for the material creep rupture of under sustained loads

φ = resistance factor that accounts for the variability and the bias of resistance

R_n = nominal strength in the end-use condition,

C = material adjustment factor that accounts for durability material exposed to exposure environment for service life of the structure

R_o = reference strength of new material as tested in the laboratory based upon the characteristic value at 80% lower confidence interval per ASTM D7290

Loads, Load Factors and Load Combinations

- Design loads, load factors, and load combinations are the same for all materials of construction.
  - Loads are expressed as expected (mean) values
  - Load factors are factors that are calculated to account for the variability of the loads so that the probability of occurrence of the factored load is low.
  - Load combinations are loads that can occur simultaneously (with load factors that depend on likelihood of such occurrence)
- ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* is the standard accepted by nearly all building codes that provides the design loads, load factors, and load combinations for any structure.
- The structure should be designed for the following one of many load combinations in ASCE 7, e.g.,

$$1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$$

where
D= Dead Load, L = Live Load, Lr = Roof Live Load, S = Snow Load, and R = Rain Load

Strength

- R_o is the reference strength of new material as tested in the laboratory.
- Having the results of tests performed on a random and representative sample of material, the reference strength is determined from probability distribution of test results as as the lower 5th percentile value of strength at 80% lower confidence per ASTM D7290.
- R_n is the nominal strength of material in the end-use condition. It is obtained as the product of reference strength and maeriala adjustment factor C ($R_n = R_o$ C).

Material Adjustment Factor C

- Adjustment factor for strength or modulus is **the mean of the retained value at the end of service life** relative to the mean of the same value obtained from tests performed on new materials.
- **Long term exposure tests** for 1,000 to 10,000 hrs are performed and retained properties are determined.
- The ratio of the mean value of retained strength to the mean value of initial strength is then computed.
- Test results are then **extrapolated to the design life** of the structure to obtain the material adjustment factor for the environment of interest.
- The value of C depends on the chemical and thermal environment to which the test specimens were subjected.

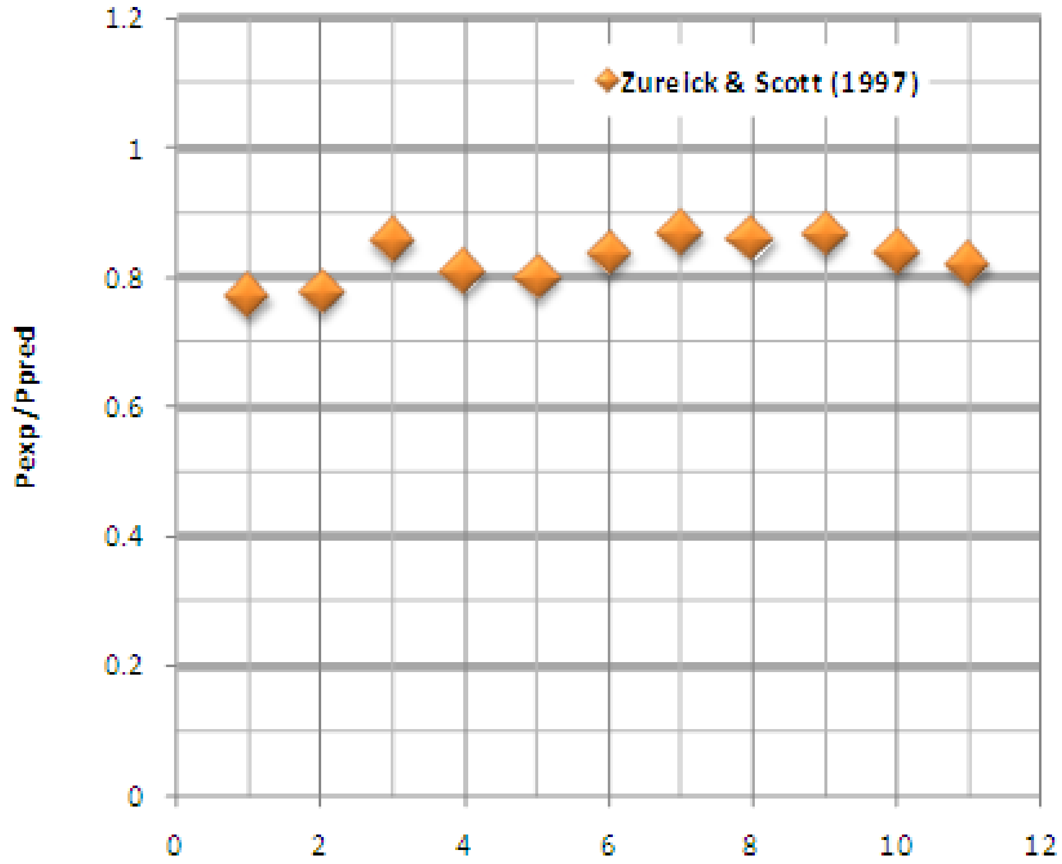
Value of Factor C for Exposure to Moisture and Temperature

- C_M = exposure to sustained moisture for 50 yrs.
- C_T = exposure to sustained temperature higher than 90°F (38°C) but less than Tg – 40°F for 50 yrs.

Reference Property		Moisture C_M	Temperature (°F) C_T for $(90 < T \leq 140)$
Vinyl Ester	Strength	0.75	1.7 – 0.008T
	Modulus	0.90	1.5 – 0.006T
Polyester	Strength	0.75	1.9 – 0.010T
	Modulus	0.90	1.7 – 0.008T

Resistance Factor, ϕ

- Test results of material resistance do not match the predictive formulas exactly. There is bias as well as scatter in the data relative to the predictive formula.
- Material resistance factor accounts for both **bias and variability** of resistance.
- Bias is determined by comparing the mean of test results with predictive formula

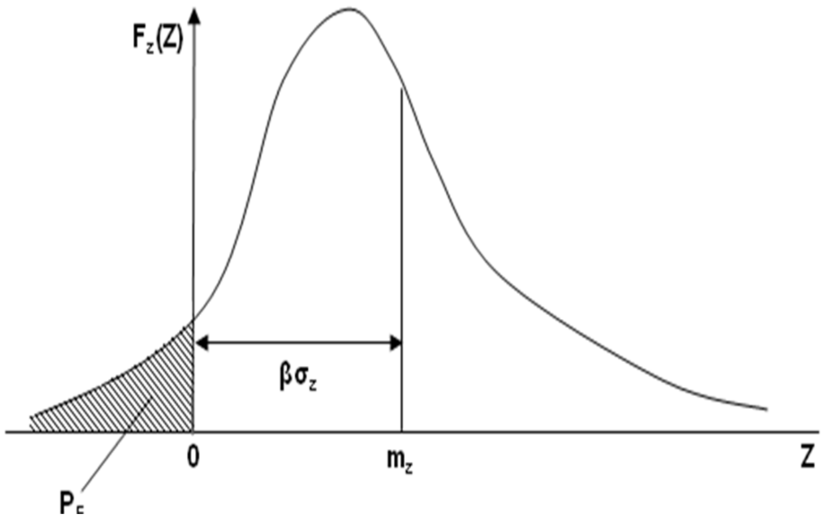


Compressive Strength of Pultruded Square Tubes

Predictive formula: $$F_{crw} = \frac{\left(\frac{\pi^2}{6}\right)\left[\sqrt{E_{L,w}E_{T,w}} + \nu_{LT}E_{T,w} + 2G_{LT}\right]}{\beta_w^2}$$

Resistance Factor, ϕ

- Procedure for determining resistance factor
  - Performing tests to failure
  - Comparing test results with the predictive formulas in the standard. Determine the bias.
  - To calculate impact of variability from test results
    - Compute standard deviation.
    - Select β = reliability index from design probability of failure selected not less than other materials of construction
    - Resistance factor = (Mean Strength) – β (Standard Deviation /Mean Strength)
  - **Reliability of designs of PFRP by this Standard is at least the same as other materials of construction, because β is not less.**



Reliability Index Values, β

Limit state	Target reliability range
Global instability	3.0 – 3.5
Local instability	3.5 – 4.0
Material strength – tension, compression, shear	3.5 – 4.0
Connection failure modes; bearing, net tension	4.0 – 4.5

Material Adjustment Factor, C

- **Design must account for the long–term environmental effects** during the service life of the structure.
- Adjustment factor for strength or modulus is **the retained value at the end of service life** relative to in the reference condition.
- **Long term exposure tests** for 1,000 to 10,000 hrs followed by strength and modulus tests are conducted on the materials.
- The results are **extrapolated to the service life** of the structure.

Material Adjustment Factor, C

- C_M = exposure to sustained moisture,
- C_T = exposure to sustained temperature higher than 90°F (38°C) but less than Tg – 40°F.
- C_{CH} = exposure to chemical environmental (high alkalinity, acidity), from the results of ASTM C581 tests for 1,000 hours, or as stipulated by Registered Design Professional.

Reference Property		Moisture C_M	Temperature (°F) C_T for ($90 < T \leq 140$)
Vinyl Ester	Strength	0.75	1.7 – 0.008T
	Modulus	0.90	1.5 – 0.006T
Polyester	Strength	0.75	1.9 – 0.010T
	Modulus	0.90	1.7 – 0.008T

Time Effect Factor, λ

- Time effects factor is the results of creep rupture tests in which test specimens are subjected to sustained loads less than their initial stength and time to failure is measured.
- The results are extrapolated to design life of the structure using regression analysis.

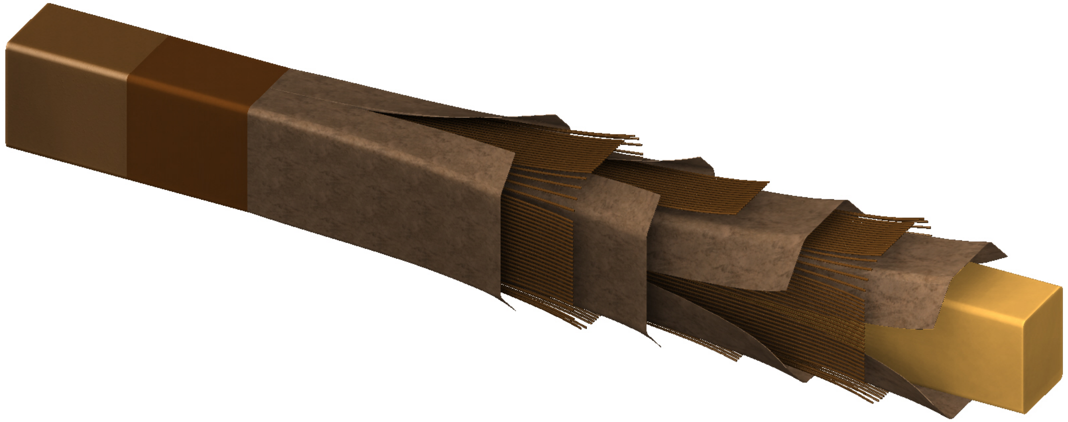
Load Combination	**λ**
1.4D (permanent load)	0.4
1.2D + 1.6L + 0.5(L_r or S or R)	0.8 when L from occupancy 0.6 when L is from storage 1.0 when L is from LL impact
1.2D + 1.6(L_r or S or R) + 1.0 L or 0.5W	0.75
All other load combinations involving full design wind and seismic loads	1.0

Section 2

Material Requirements

Material Qualifications

- The material and the design must meet certain criteria
  - ✓**Fiber system**
  - ✓**Resins** (polyester, vinyl ester, epoxy)
  - ✓**Other Constituents** (fillers, promoters, accelerators, inhibitors, UV agents, pigments)
  - ✓**Minimum physical (e.g., Tg) and mechanical properties** of laminate
  - ✓**Fire, smoke and toxicity** requirements
  - ✓**Durability** and environmental effects.
  - ✓**Time effects**



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Example of Fiber System Requirements

- ***Fiber Form****:* All forms including rovings; woven, braided, or stitched fabrics; continuous strand mats, and chopped strand mat.
- ***Fiber Orientations***: Each element of a pultruded FRP member shall have reinforcing fibers oriented in a minimum of two directions separated by a minimum of 30 degrees.
- ***Fiber Volume Fraction***: The minimum total fiber volume fraction of each pultruded FRP element shall not be less than 30%.
- ***Percentage of Fiber Orientation***: The total fiber volume reinforcement in the longitudinal direction shall be at least 30% for shapes and 25% for plates.
- ***Fiber Fraction Through Multiple Element Edge***: When multiple elements share a common edge, 50% of the non-roving reinforcement of the element shall extend through the junction of the connecting the elements.
- ***Minimum Tensile Strength of Fiber****:* The characteristic value shall be not less than 290 ksi when tested according to ASTM D2343.

Section 3

Design of Members

Design of Members

- The requirements for determining the capacity of pultruded FRP structural shapes are discussed in six chapters as follows
- Members
  - subjected to **tension** through the centroid of the transformed cross section.
  - subjected to **compression** through the centroid of the transformed cross section.
  - subjected to **flexure and shear** resulting from loading transverse to their axes
  - subjected to **axial force and bending** and **axial force, bending, and torsion**.
  - Design of pultruded FRP **flat plates** subjected to flexure, through-the-thickness shear, and in-plane loading.

Design of Compression Members

Design of a PFRP member subjected axial compression is governed by

- **Rupture of Members in Compression**: Compression members are designed for rupture and allows for stress risers.
- **General Buckling of Member:** Accounting for initial imperfection, but axial force shall not exceed 30% of compressive strength over the gross section.
- **Local Buckling Strength of Flanges and Webs** of PFRP Sections**.**
- **Slenderness Ratio** of a compression member is bounded.

Design of Compression Members

- **Scope**:

  Design of pultruded FRP members subjected axial compression through the centroid of cross section.

- **Design of Members for Compression**:

  Compression members are designed for both strength and serviceability

$$P_u \leq \lambda \phi P_n \leq 0.7 \lambda F_L^c A_g$$

Where $\phi P_n = \phi F_{cr} A_g$ and

$$P_s \leq \varphi_0 \frac{\pi^2 E_L}{\left(\frac{KL_e}{r}\right)^2} A_g \leq 0.3 F_L^c A_g$$

F_{cr} = Critical buckling strength

P_s = Compression force due to serviceability load combinations

A_g = Gross area of cross section

E_L = Minimum characteristic value of the modulus of flange or web, adjusted for end use condition.

$F_L{}^c$ = Minimum characteristic value of compressive strength of flange or web, adjusted for end-use condition

$\emptyset_o$ = 1-500$\frac{\delta_0}{L}$ = Reduction factor that accounts for the initial out-of-straightness $\frac{\delta_0}{L}$

$\frac{KL_e}{r}$ = Compression member effective slenderness ratio $\leq 1.4\sqrt{\frac{E_L A_g}{P_D}}$ where P_D = compression force due to unfactored DL.

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Design of Compression Members (cont.)

Determination of Critical Buckling Load

- **Symmetric I-, Tee-, Equal Leg Angle-, Rectangular-, and Round-Sections:** Design of each section may be governed by one or more of the following limit states:
  - Euler buckling in both directions based on transformed properties
  - Outstanding flange buckling (one side simply supported or restrained and the other side is free)
  - Flange buckling of rectangular tubes as simply supported orthotropic plate
  - Web buckling as simply supported orthotropic plate for symmetric I-sections and rectangular sections
  - Torsion and warping of T-sections
  - Buckling of orthotropic circular tubes
- **Buckling of Other Sections:** Nominal strength of all other section sections shall be determined by testing or rational analysis.

Approach to Critical Buckling Strength Calculation

- Design of members in compression and bending are governed by critical buckling strength of their flanges and webs in compression.
- Two approaches are recognized for buckling of the member depending on restraining effects of components (i.e., web stiffness restraining buckling strength of flange).
- FCAPS adopted the simpler approach based on neglecting the restraining effect of the web for the provisions of the sections on compression and flexure of members.
- An optional approach based on including the restraining effect of the web on flange buckling strength shall be provided in the Appendices of these sections.

Design of member for Flexure and Shear

Scope: Design for flexure and shear of pultruded FRP members loaded transverse to their axes.

Design of Members for Flexure:

$$M_u \leq \lambda \phi \, M_n$$

M_u = Required factored flexural strength

$\emptyset$ = Resistance factor for flexure

λ = Time effect factor

$\emptyset M_n$ = Nominal flexural strength

(a) material rupture, $\phi M_n = \phi \, S_t \, F_{cr}$

(b) local buckling, and

(c) lateral-torsional buckling $\phi M_n = \phi C_b \dfrac{\pi}{L_b} \sqrt{[E_{L,f} I_y G_{LT} J + I_y C_w \left(\dfrac{\pi E_{L,f}}{L_b} \right)^2}$

Design of member for Flexure and Shear (Cont.)

Design of Members for Shear:

$$V_u \leq \lambda\phi\, V_n$$

V_u= Required shear strength

V_n = Nominal shear strength, minimum from limit states of

(a) material rupture, and

(b) shear buckling.

Design of Members for Concentrated Forces

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

R_u = Required strength of members due to a concentrated force

R_n= Nominal strength due to concentrated force, minimum from limit states of

(a) tensile rupture,

(b) web crippling,

(c) web compression buckling,

(d) flange flexural failure

Section 4

Design of Connections

Design of Bolted Connection

- **Scope**

Design of *bearing-type* and *tension-type* bolted connections for pultruded FRP shapes and plates with FRP and/or metallic connecting elements (e.g., gussets, splice plates, and angles), and steel or stainless steel bolts.

The types of connection covered shall be in the form of lap shear configurations with the loading principally in-plane of the connecting members. Also covered are simple frame connections in the forms of a single or a pair of clip angles. Slip-critical connections are not permitted. All other connection types shall be designed by testing.

- **Connection Design**

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

R_n = Nominal connection strength in the end-use condition, considering all possible critical failure modes factored by C_Δ.

C_Δ = s/s_{min} if pitch spacing, *s*, is less than $s_{min;}$ otherwise C_Δ = 1.0.

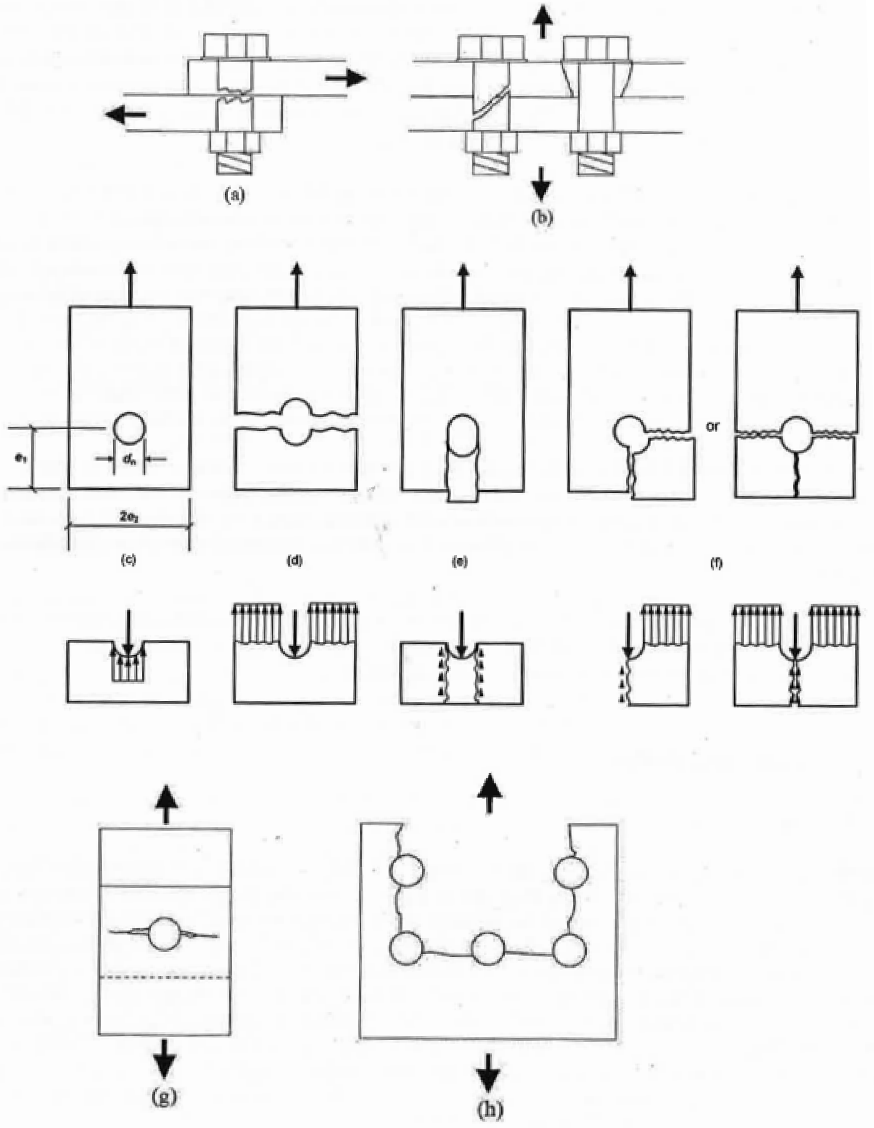
Design of Bolted Connection

- Design requires identifying the failure plane and evaluating the strength corresponding to all limit states for a single bolt failure.
- Identifying block shear planes and limit states and evaluation procedure for block shear loading situations with a single row of bolts, multiple rows of bolts, gusset plates.

Design of Bolted Connection (Cont.)

Bolted Connection Limit States

(a) bolt tension and shear
(b) pull-out tension
(c) pin bearing
(d) net tension
(e) shear-out
(f) cleavage
(g) net tension splitting
(h) block shear limit state with multiple rows of bolts



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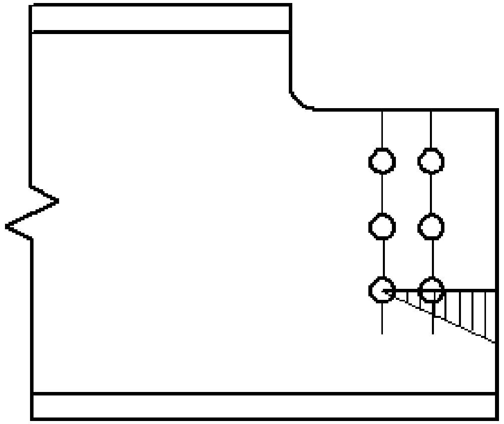
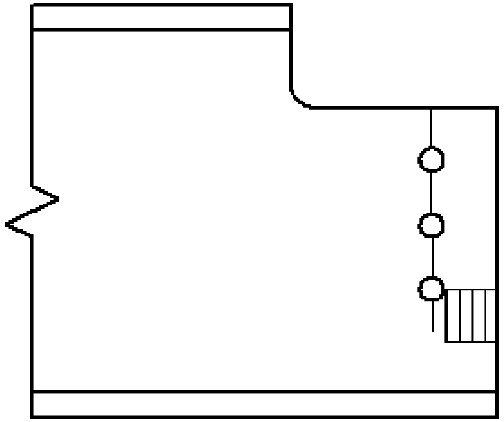
Design of Bolted Connections (Cont.)

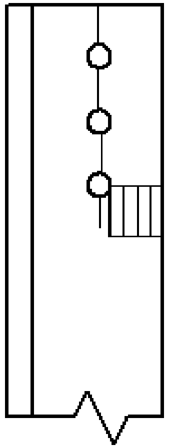
- Block shear loading situations with direct stress distributions at failure plane
- multiple row beam
  - end connection
- single row beam
  - end connection
- gusset plate
- angle ends



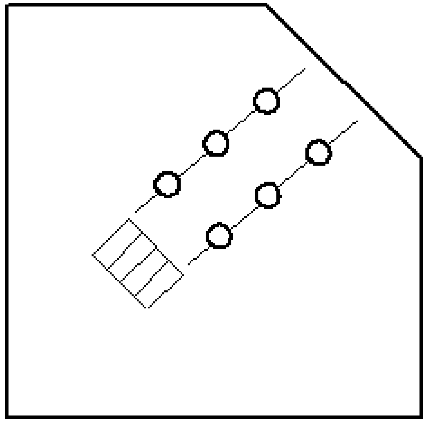
Multiple-row beam end connections



Single-row beam end connections



Angle ends



Gusset plates

Section 5

Seismic Design

Seismic Design

- The seismic design provisions were needed for completeness and to allow structural engineers to make use of the high strength-to-weight ratio of this product.
- Earthquake load effect, E, are determined per *ASCE 7.*
- Designs by this standard meets the **General Structural Integrity** provisions of ASCE 7.
- To resist lateral seismic loads, PFRP structures **are required to be designed with braces**.
- Seismic Design Parameters of PFRP structures are provided. These parameters **must be incorporated in standards and building codes**.

Seismic Design (Cont.)

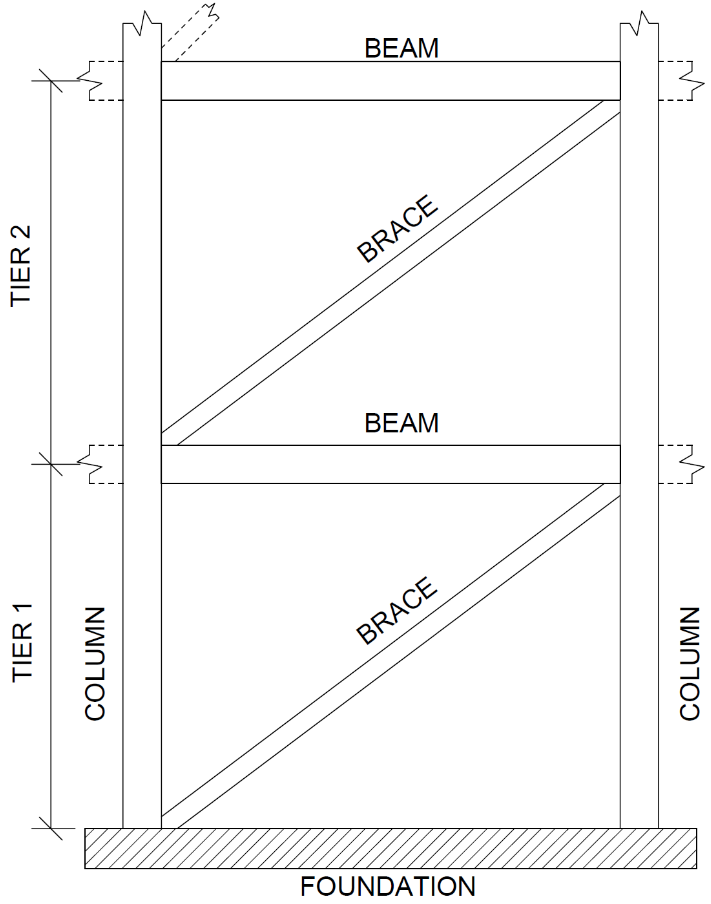
Table 9.1.2 Seismic Design Parameters

System	R	C_d	Ω_0	Design Reference
Generic FRP	1	1	1.5	9.2.1
Multi-tier Braced Frame	1.5	1.5	1.5	9.2.2
Enhanced Connection Strength Braced Frame	2	2	2	9.2.3
Ordinary Braced Cooling Tower	2	2	2	9.2.4

Section 12.8.1.3 of ASCE 7 shall not apply_for structures designed according to this standard.

Seismic Design (Cont.)

- To Resist lateral seismic loads, pultruded FRP structures are required to be designed with braces.
- Ordinary braced cooling towers can be designed as follows:
  - ➢ Columns are continuous from the base to the top level of the structure.
  - ➢ Beams are continuous the full length of the structure in each direction.
  - ➢ Columns and beam splices shall develop 50% of the flexural capacity and 25% of the tensile capacity of the column and beam.
  - ➢ Beams and columns are aligned in an orthogonal grid with at least four lines of columns and three tiers of beams
  - ➢ Every line of columns and beams in each direction is braced with diagonal braces.
  - ➢ Centerlines of columns, beams, and braces lie within one vertical plane.
  - ➢ Effective seismic weight of water film and fill is permitted to be reduced based on testing or rational analysis



Section 6

Conclusions

Conclusions

This presentation highlights the major accomplishments of this new standard.

- ASCE/SEI 74 will impact the design, manufacture, and use of pultruded composites structures in buildings, bridges, industrial structures, prefabricated components or structural systems, and art works.

- ASCE/SEI 74 will provide engineers, architects, designers, and composite manufacturers the ability to provide the most economic design for pultruded composite structures with safety, reliability, and durability comparable to the other materials of construction.

- ASCE/SEI 74 will promote use of pultruded FRP in new structures that demand materials that have very high strength to weight ratio or can resist adverse environment that other construction materials such as steel or reinforced concrete fail to perform.

- ASCE/SEI 74 has shown where more research and data from carefully conducted tests are needed.

Conclusions (Cont.)

- I hope this presentation has succeeded to convey the key parts of the content, and to demonstrate that mandatory provisions and commentary of the new standard can allow you to design constructed facilities using FRP composites safely and efficiently.
- It took three years of effort to draft the Pre-standard, review by a committee of renowned researchers, and trial design by practicing engineers, followed by 43 ballots over a span of 10 years in FCAPS Committee of ASCE to take this first step.
- This standard, like any other standard, will mature as more research and data become available by industry, academia, and structural engineers and designers, and as innovative applications of pultruded FRP will come to existence.

Thank you, Questions?

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