Pultrusion Conference 2021

Seismic design considerations and connection prying forces in a large, multi-story pultruded FRP structure in a region of high seismicity

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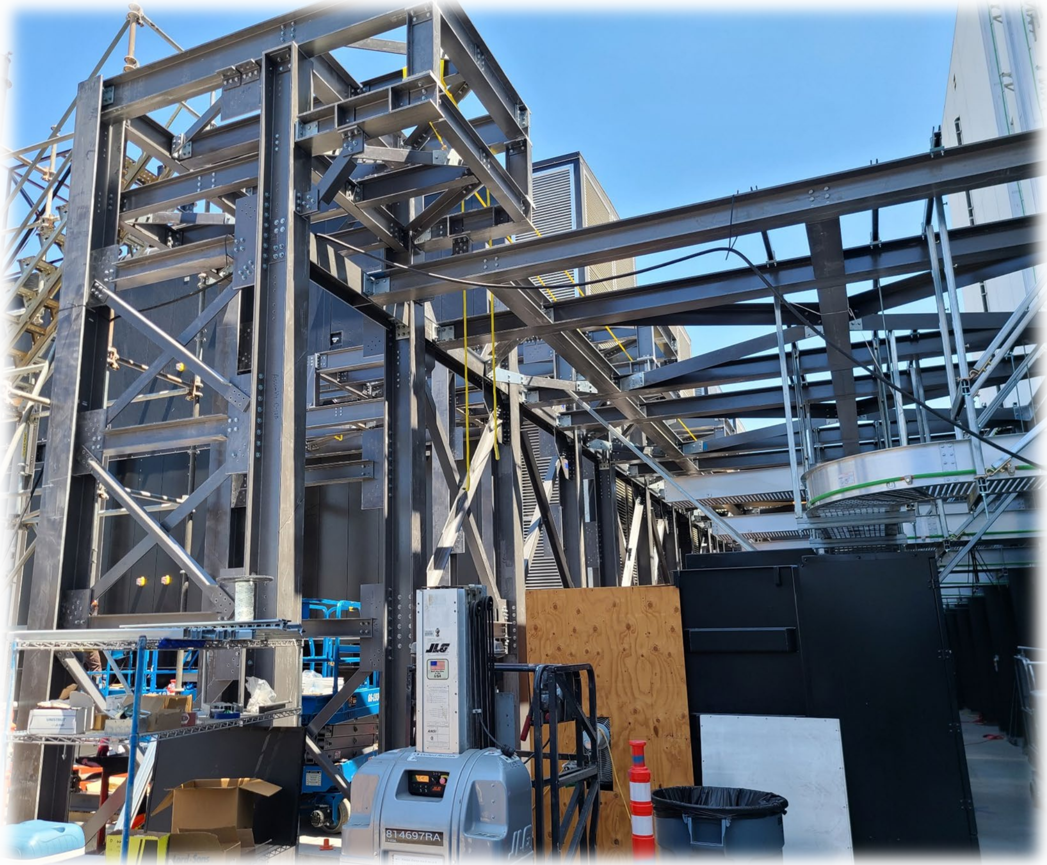
Summary

Datacenter Equipment Yard: Santa Clara, CA



Pultruded FRP in the "Mission Critical" sector

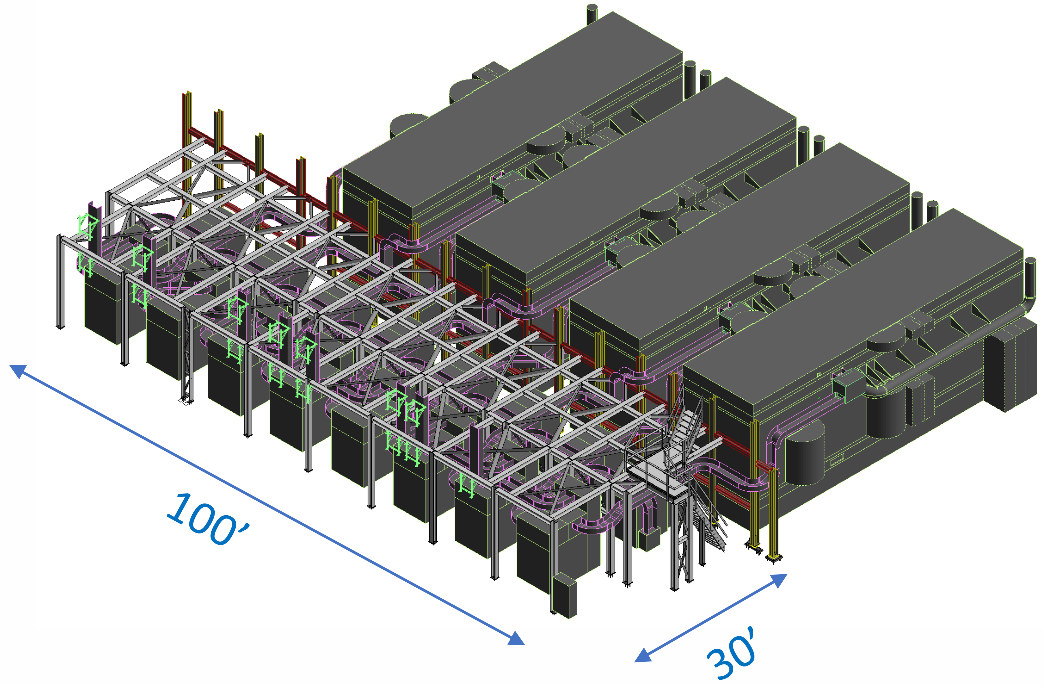
Key Stats

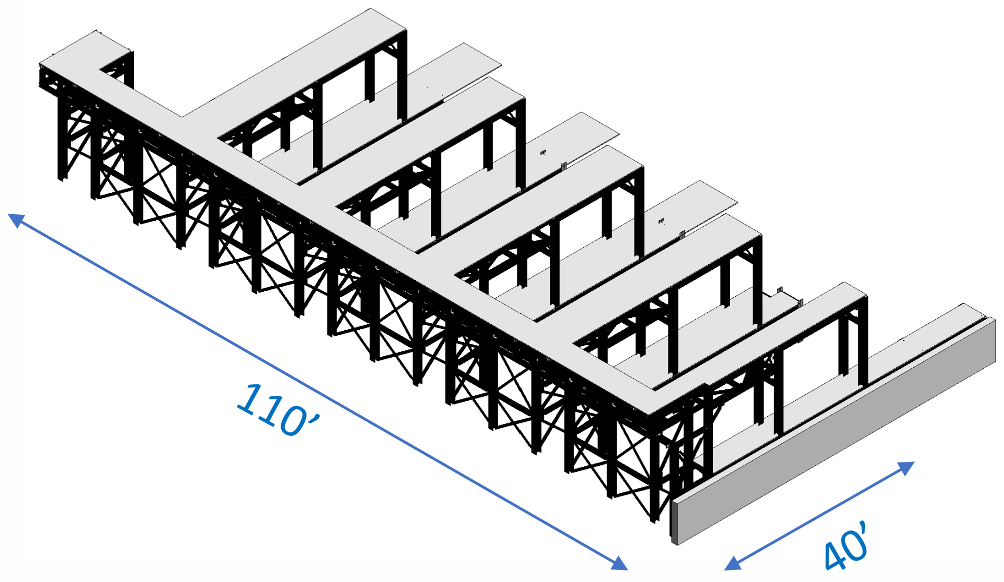
- ✓ Two stories
- ✓ 20+ ft tall
- ✓ 7,000 square feet
- ✓ All FRP (beams, columns, braces and majority of connection clips)
- ✓ Extensive BIM coordination w/ clearances of 1/8 in.
- ✓ Largest freestanding FRP structure in a region of high seismicity (in terms of bulk weight) to our knowledge

Location

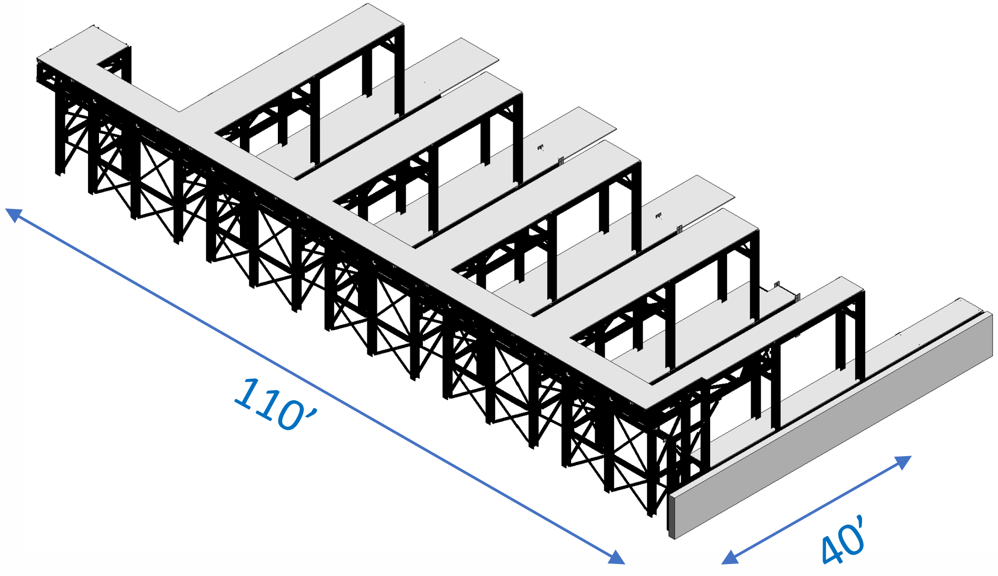
- The Data Center is located in Santa Clara, CA:
  - Densely built-up area on densely built-up site (real estate is premium)
  - Straddled by the San Andreas, Hayward and Calaveras faults
  - High level of seismicity

Geometry





- The structure is composed of two main portions (~7000 sq ft footprint)
  - The cable bus support
    Footprint ≈ 100 ft x 30 ft
    Height ≈ 12 ft
  - The generator platform
    Footprint ≈ 110 ft x 40 ft
    Height ≈ 20 ft
- Total weight of the structure: 120 kips
  (FRP weight is ~25% of steel)



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Why FRP?

- Increasingly competitive lead times versus steel
- Low specialization required for typical construction scenarios
- Resistance against weathering and corrosion (secondary on this project)

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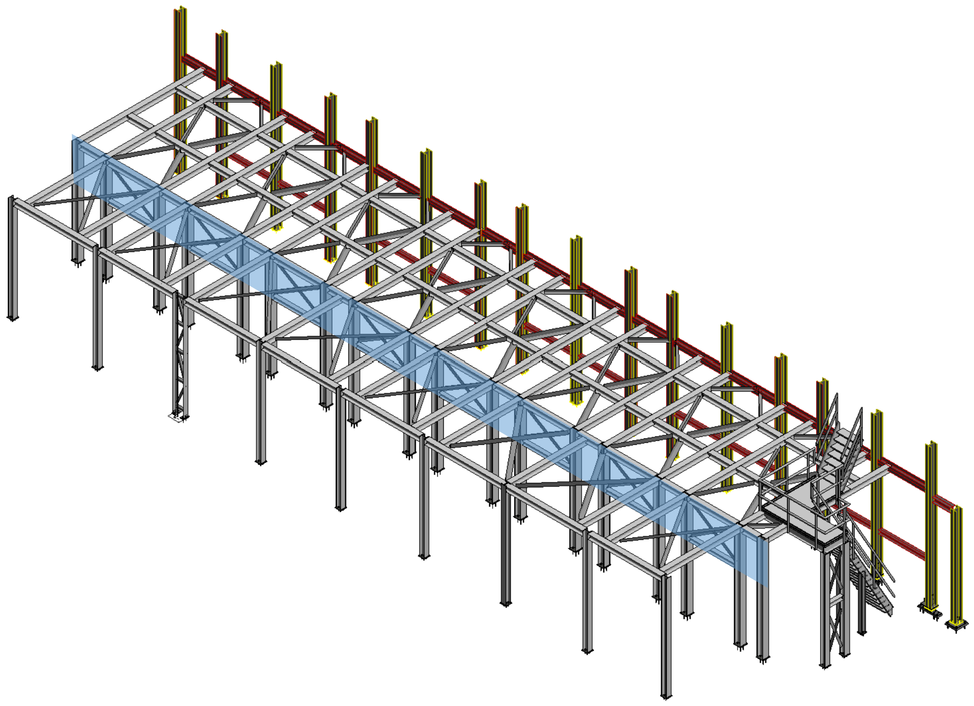
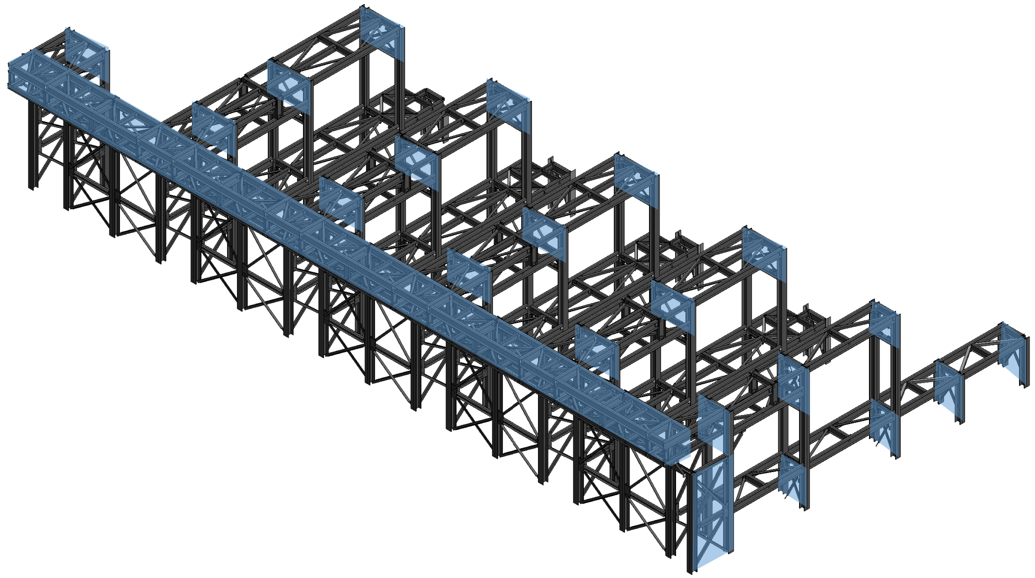
Structural System





- The cable bus support structure:
  - Single story
  - Vertical bracing in E-W direction only
  - Horizontal bracing at the top
- The generator platform structure:
  - Two stories
  - Vertical bracing both in E-W and N-S direction
  - Horizontal bracing at both levels
  - 3D truss system with kickers for the walkway

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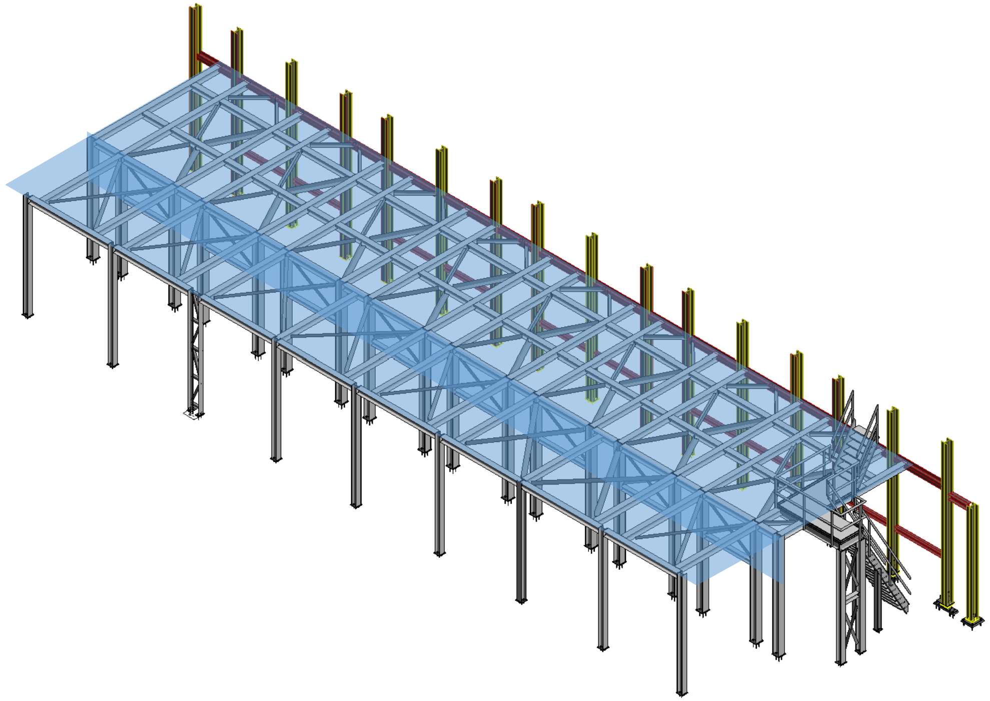

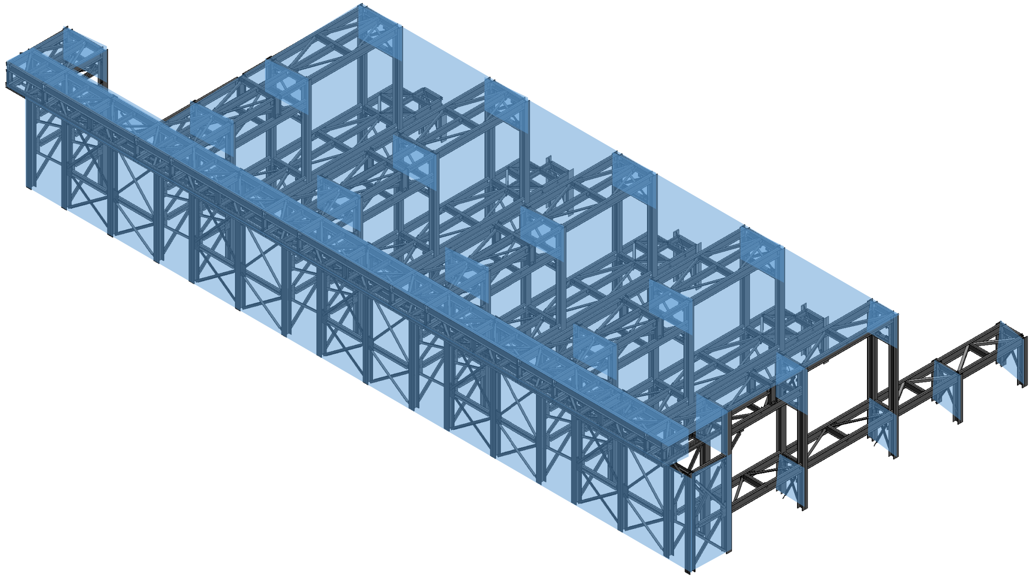

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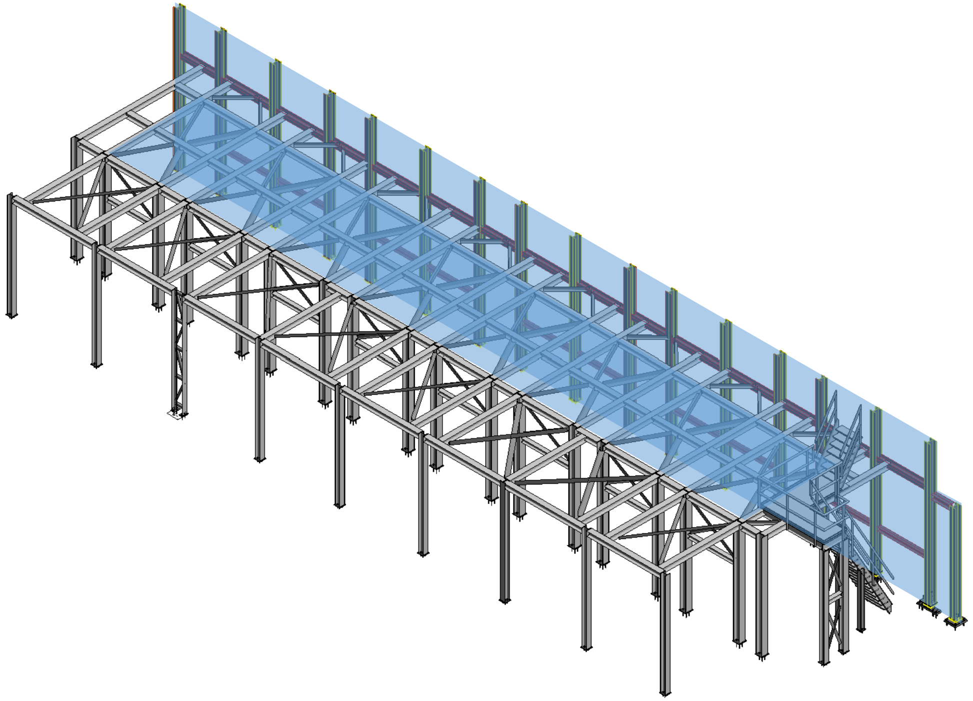
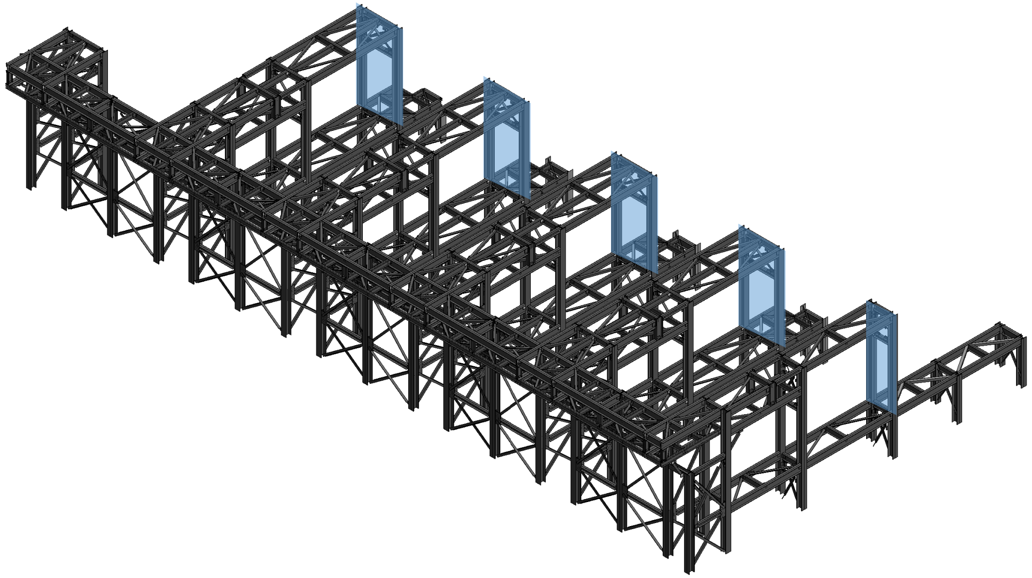
Design Challenges





- High heat of exhaust warranted distancing from the horizontal FRP braces
- Reduced FRP allowable strength where applicable
- Built-up FRP shapes with use of adhered FRP cover & doubler plates
- Use of steel connections only when strictly necessary (i.e., skewed connections and heavily loaded connections)

Risk Category and Site Class

Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures designated as essential facilities	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released[a]	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures	

ASCE 7 – Table 1.5-1

Table 1.5-2 Importance Factors by Risk Category of Buildings and Other Structures for Snow, Ice, and Earthquake Loads[a]

Risk Category from Table 1.5-1	Snow Importance Factor, I_s	Ice Importance Factor—Thickness, I_i	Ice Importance Factor—Wind, I_w	Seismic Importance Factor, I_e
I	0.80	0.80	1.00	1.00
II	1.00	1.00	1.00	1.00
III	1.10	1.25	1.00	1.25
IV	1.20	1.25	1.00	1.50

ASCE 7 – Table 1.5-2

- Risk category IV was selected voluntarily by the owner:
  - But data centers are generally considered “critical infrastructure” by US gov.

TABLE 11.6-1 Seismic Design Category Based on Short-Period Response Acceleration Parameter

Value of S_{DS}	Risk Category: I or II or III	Risk Category: IV
$S_{DS} < 0.167$	A	A
$0.167 \le S_{DS} < 0.33$	B	C
$0.33 \le S_{DS} < 0.50$	C	D
$0.50 \le S_{DS}$	D	D

ASCE 7 – Table 11.6-1

Risk Category and Site Class

- Risk category IV was selected voluntarily by the owner:
  - But data centers are generally considered “critical infrastructure” by US gov.
- Soil site class = D
- Seismic design category (SDC) = D

Seismic Design Coefficients

Seismic design coefficient per material and structural system	Generic FRP	Multi-tier braced FRP frame	Steel ordinary concentrically braced frames	Steel special concentrically braced frames
Response modification coefficient, R	1.00	1.50	3.25	6.00
Deflection amplification factor, C_d	1.00	1.50	3.25	5.00
Overstrength factor, Ω_0	1.50	1.50	2.00	2.00

Base shear decrease

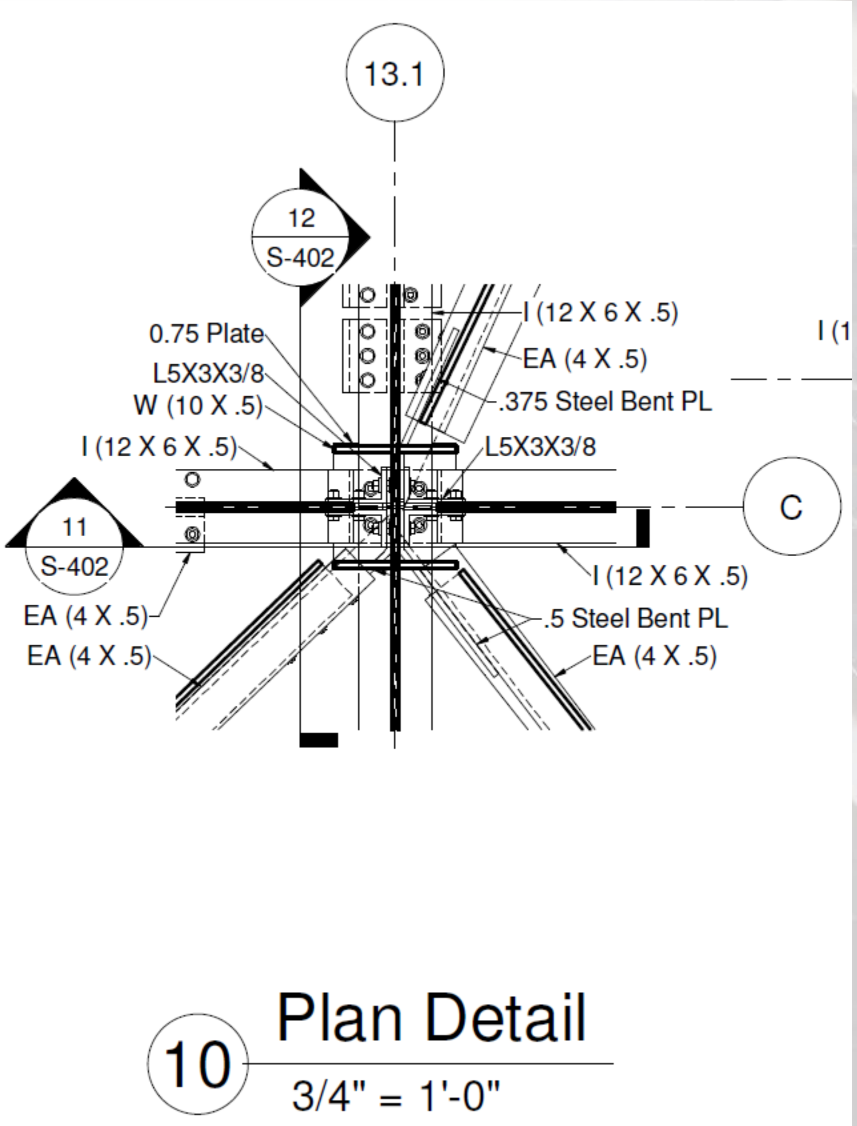
Component demand increase

- The cable bus support structure:
  Identified as a generic FRP per the forthcoming standard for FRP design
- The generator platform structure:
  Identified as a multi-tier braced frame per the forthcoming standard for FRP design

(The base shear of a building is inversely proportional to the response modification coefficient, R, and directly proportional to the weight, W. Lower R results in larger seismic demand, while lower W results in lower seismic demand.)

CONNECTIONS

- Types of FRP connections
- Limit states
- Prying effects on FRP



Types of FRP connections

- Ductility of steel connections moot because plasticity of steel connections unlikely to occur prior to FRP fracture
- Therefore, steel only used in skewed connections and when required for strength
- Three FRP connection scenarios were prominent in the project:
  - WT-shape connections for braces (lower loads)
  - Gusset plate connections for braces (higher loads)
  - Double angle connections for beams

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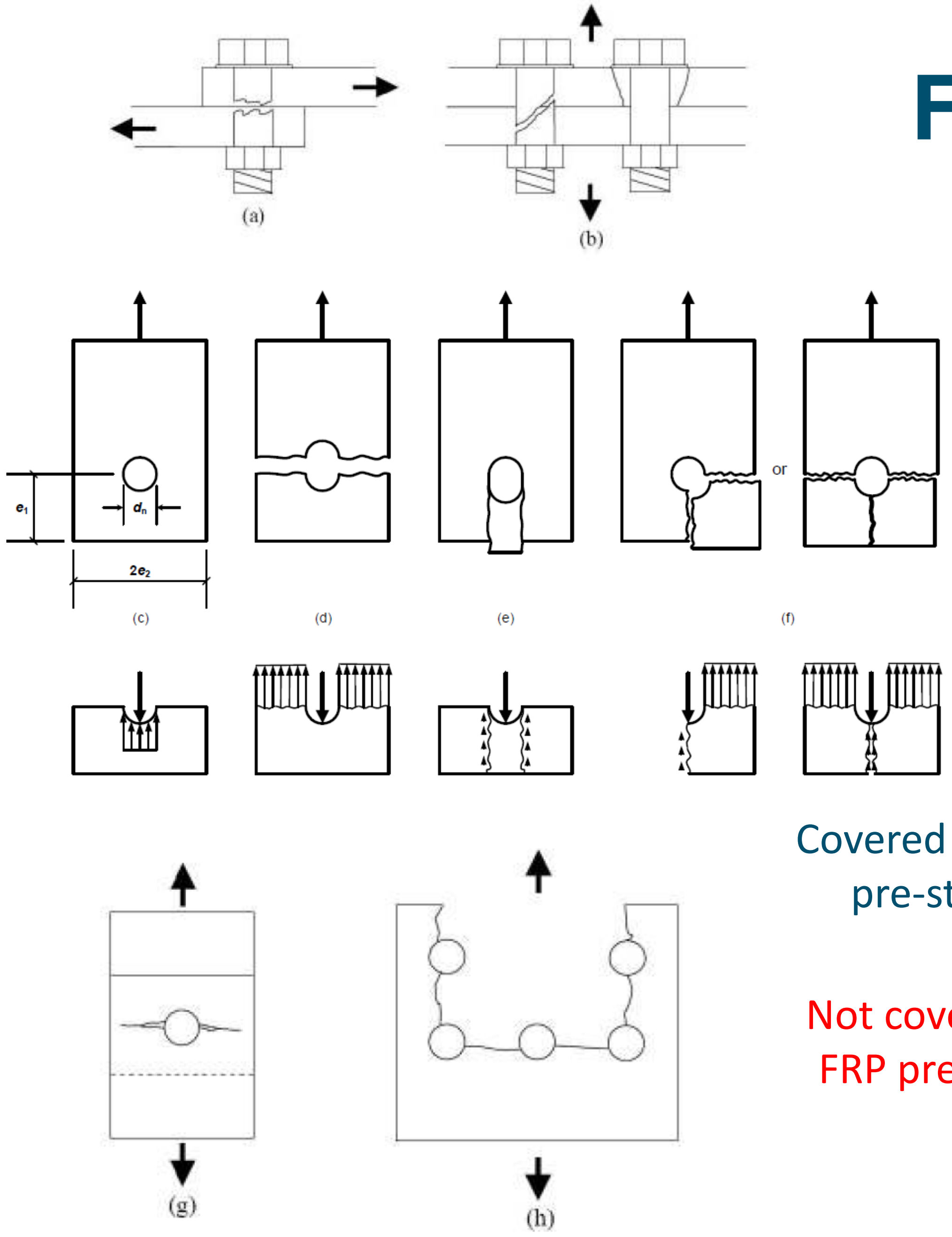
FRP connections: Limit states



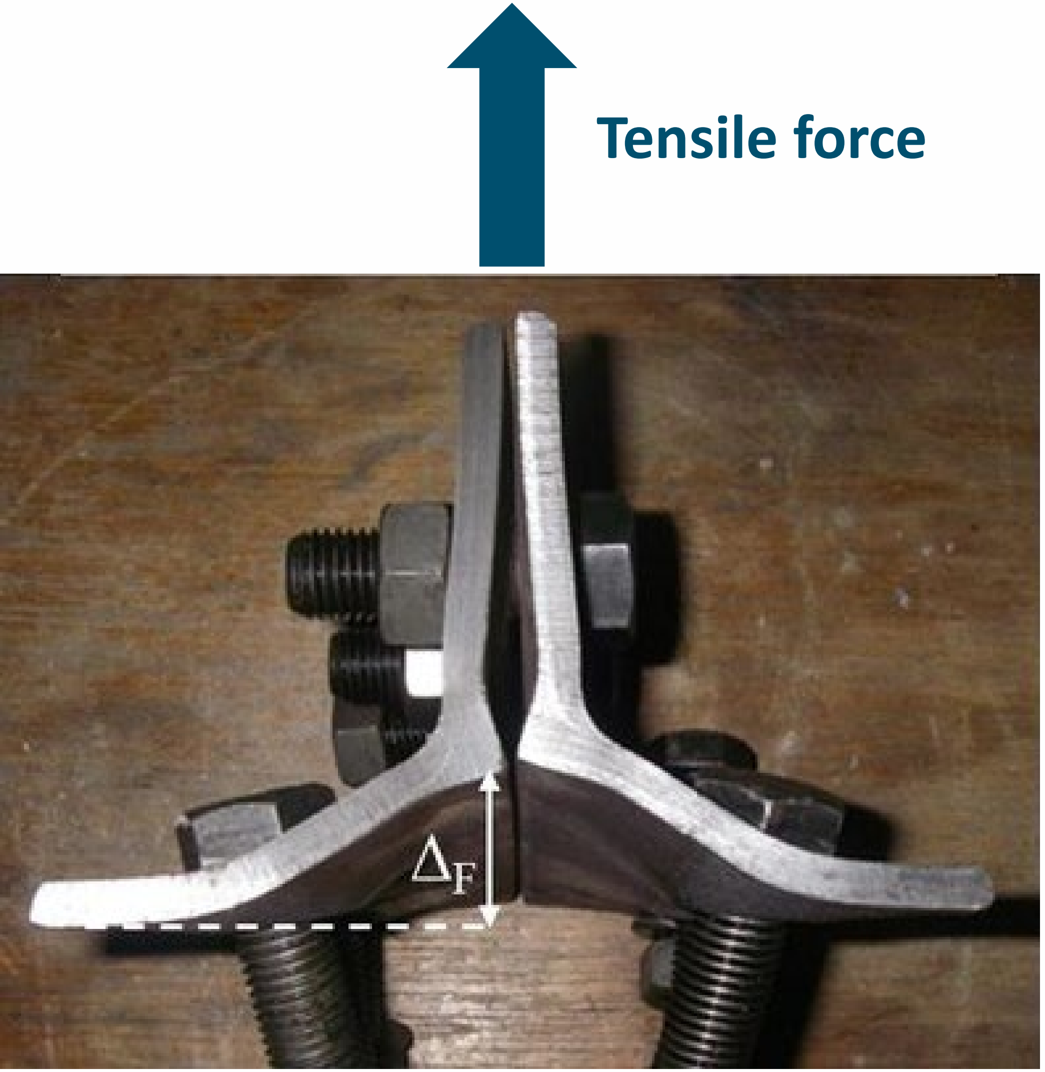
Pre-Standard for pultruded FRP design – Figure C8.3

Covered in the FRP pre-standard

Not covered in the FRP pre-standard

- Tension and shear strength of the bolts
- Tension (through-the-thickness) strength
- Pin-bearing strength
- Net tension strength at first bolt row
- Shear-out strength
- Block shear strength
- Failure due to prying of the connector

Prying Effects on FRP



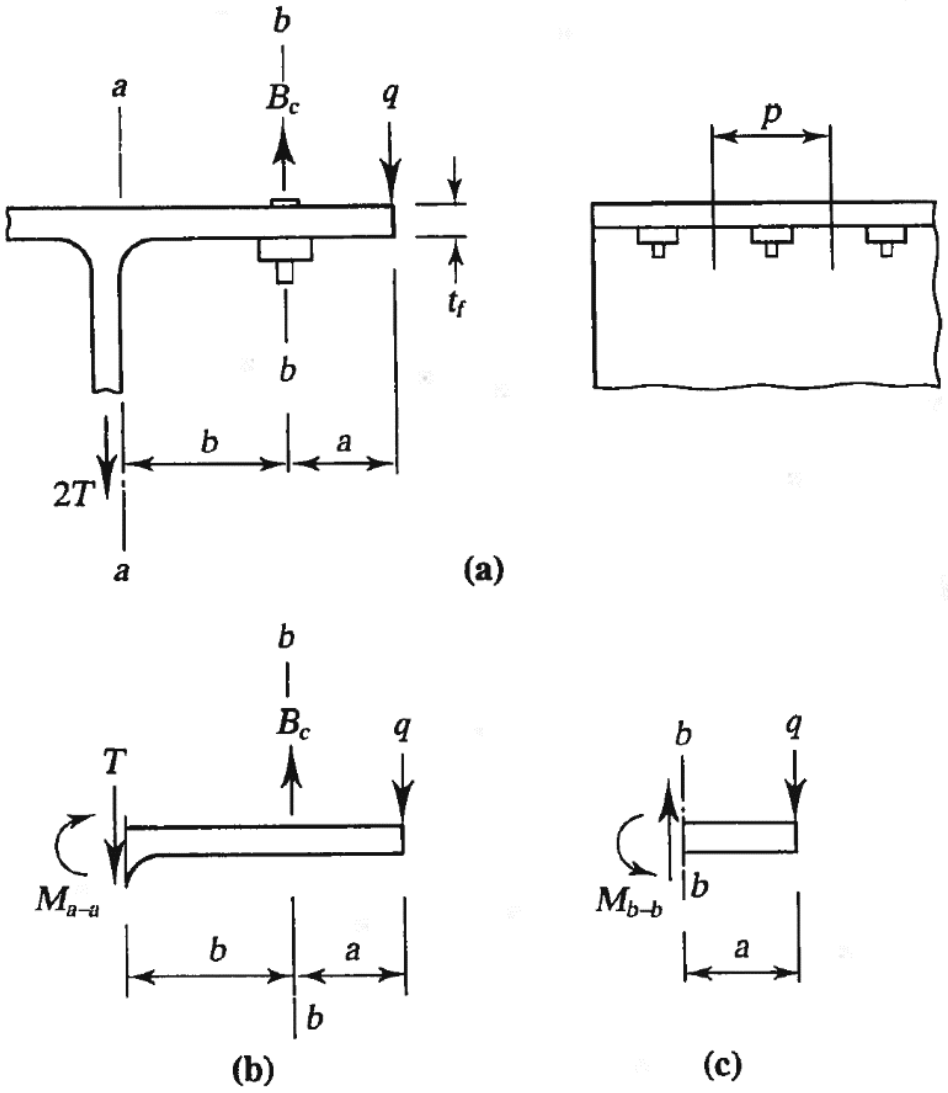
The image is of steel clips. The mechanism for FRP would be similar but with less deformation prior to fracture.

Most beams part of lateral load resisting system; therefore had large axial loads and prying was the often the governing limit state.

No prying action guidance for FRP exists.

Concern is bending rupture of a leg of the FRP connection.

Prying Effects on FRP



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$$Tb' - M_{a-a} = qa' \text{ (Figure b)} \quad (1)$$

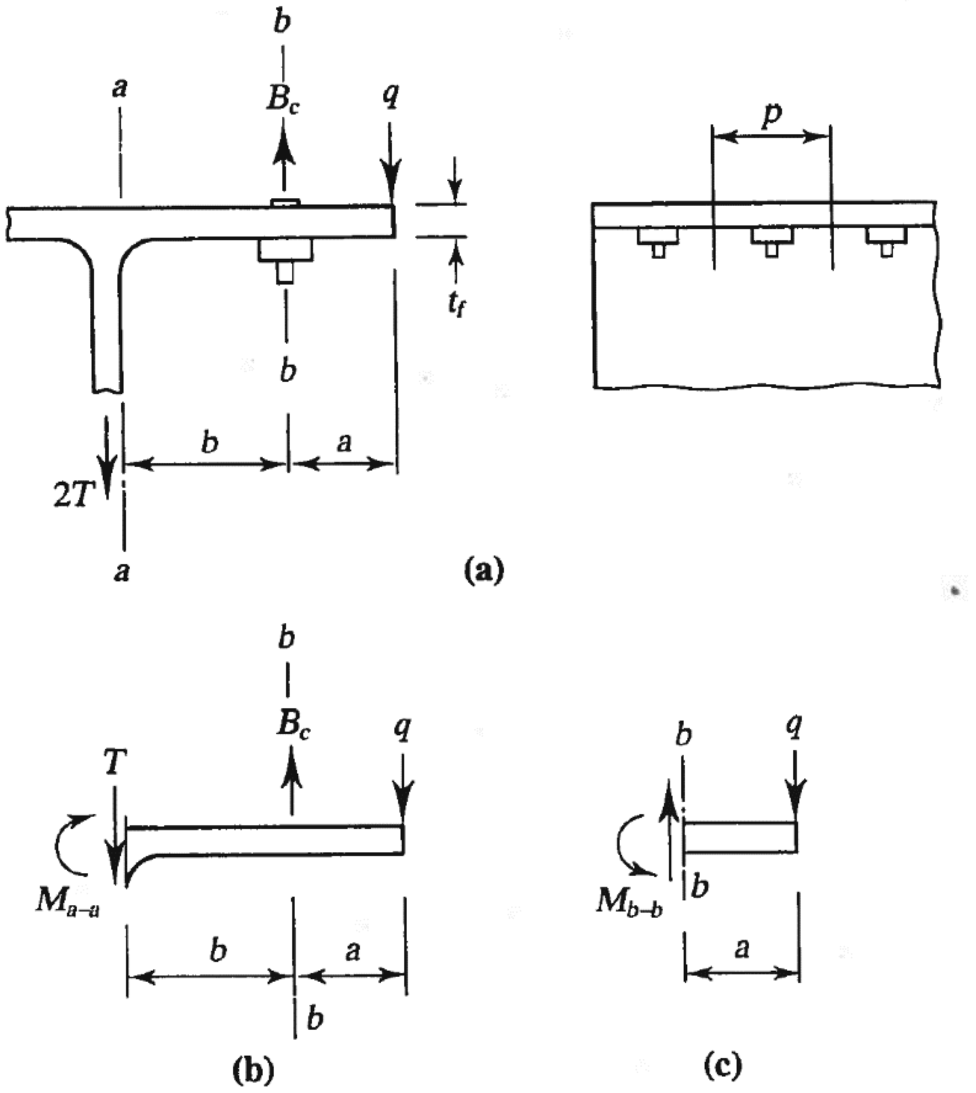
$$M_{b-b} = qa' \text{ (Figure c)} \quad (2)$$

$$\alpha = \frac{M_{b-b}/(p-d')}{M_{a-a}/p} = \frac{M_{b-b}}{M_{a-a}}\left(\frac{1}{1-\frac{d'}{p}}\right) \quad (3)$$

$\delta = 1 - \frac{d'}{p}$ where d' is the diameter of the bolt hole

$$\alpha\delta M_{a-a} = M_{b-b} \quad (4)$$

Prying Effects on FRP



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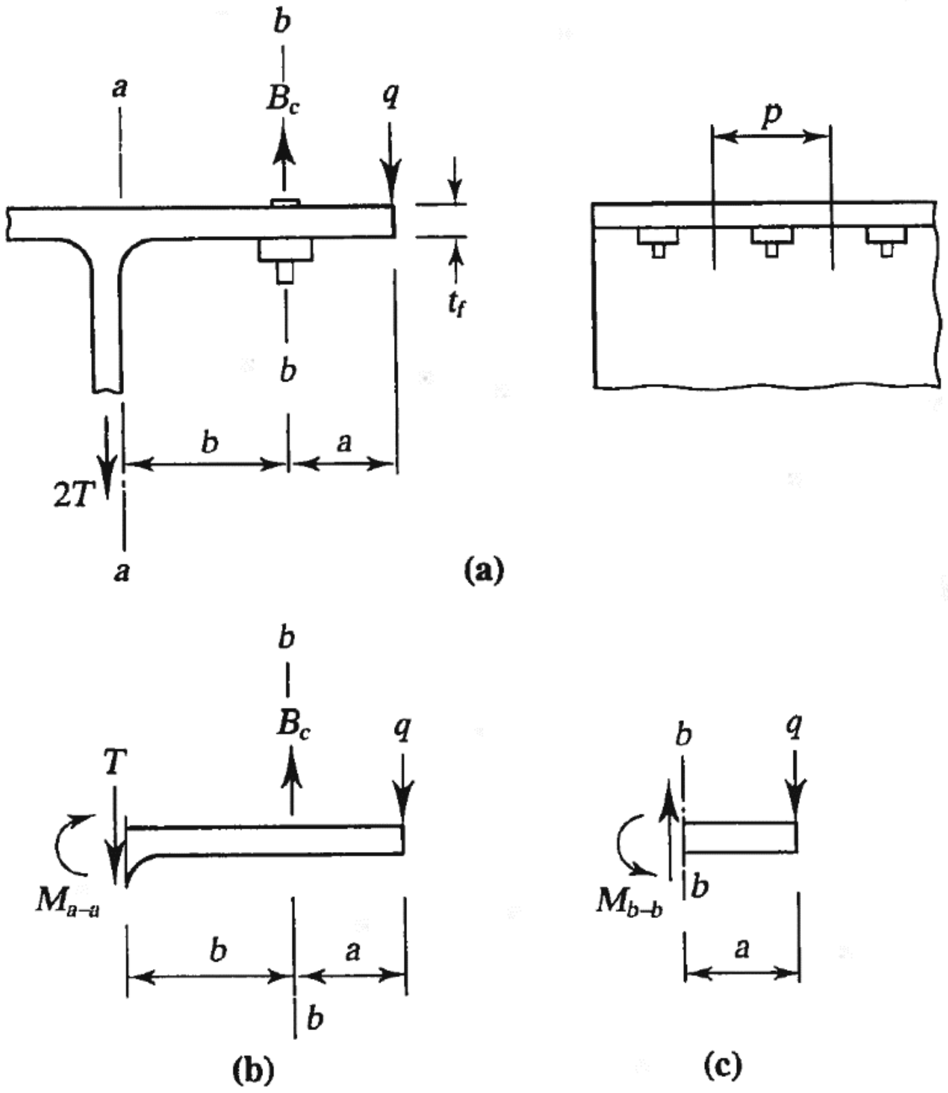
Combine (1), (2), and (4)

$$M_{a-a} = \frac{Tb'}{1 + \alpha\delta} \tag{5}$$

Note that $M_{a\text{-}a}$ corresponds to the "weak-axis" bending strength of a leg of the connection angle. Therefore, transverse material properties are assumed. Due to the lack of test data on post-elastic behavior of FRP, elastic material limit was utilized.

$$M_{a-a} < \boldsymbol{\varphi_b} M_n = \boldsymbol{\varphi_b S_y F_t{}^T} = \boldsymbol{\varphi_b} \frac{pt^2}{\mathbf{6}} \boldsymbol{F_t{}^T} \tag{6}$$

Prying Effects on FRP



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Combine (5), and (6)

$$t > \sqrt{\frac{\mathbf{6}Tb'}{\boldsymbol{\varphi_b} p \boldsymbol{F_t}^{\boldsymbol{T}}(1+\alpha\delta)}} \qquad (7)$$

Unlike steel, no ductility can be currently assumed for FRP due to lack of relevant test data combined with known brittleness of material.

Limitations of FRP in the Project

- Use of steel bent plates and steel clip angles for some of the highly loaded connections
- Steel base plates

Successes of FRP in the Project

- Cost
- Speed
- Regulatory approval of FRP in high seismicity
- Owner acceptance of FRP in high seismicity
- Implementation of new ACMA design standard seismic coefficients
- Development of a prying capacity equation specific to FRP

Future Research Needs

- Tests for prying effects on FRP connections
- Tests for inelastic behavior of pultruded FRP framing
- FEMA P-695 methods to establish (less conservative?) seismic design coefficients (i.e., R, C_d, and Ω_0)

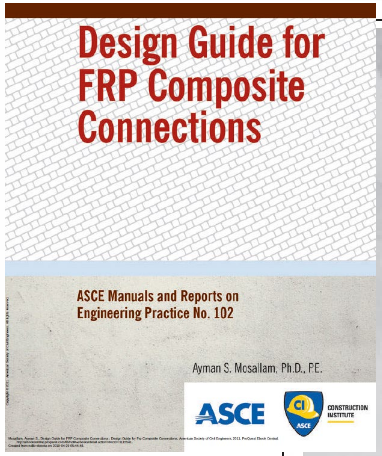

Figure 7-76. Seismic evaluation of 3-D PFRP frame structure with PFRP gratings.
Source: Mosallam (2000).

Questions?

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