North American Pultrusion Conference

Advancements in Pultruded FRP Connection Design and Detailing

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ACMA American Composites Manufacturers Association | EPTA

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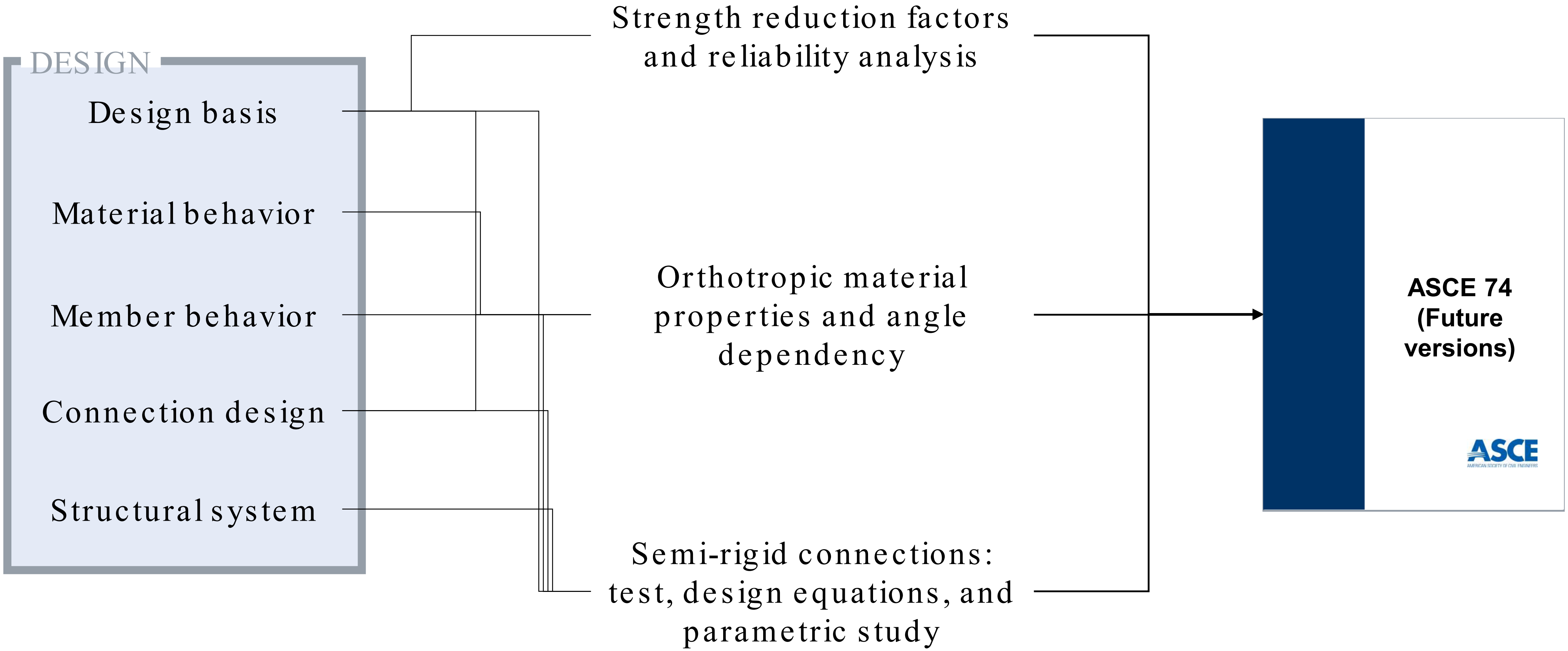
David Pirchio, PhD, MSCE, MSAE

01/2020 – Current: Project Engineer at Frost Engineering & Consulting – Specialization in design of pultruded fiber reinforced polymer (FRP) structures

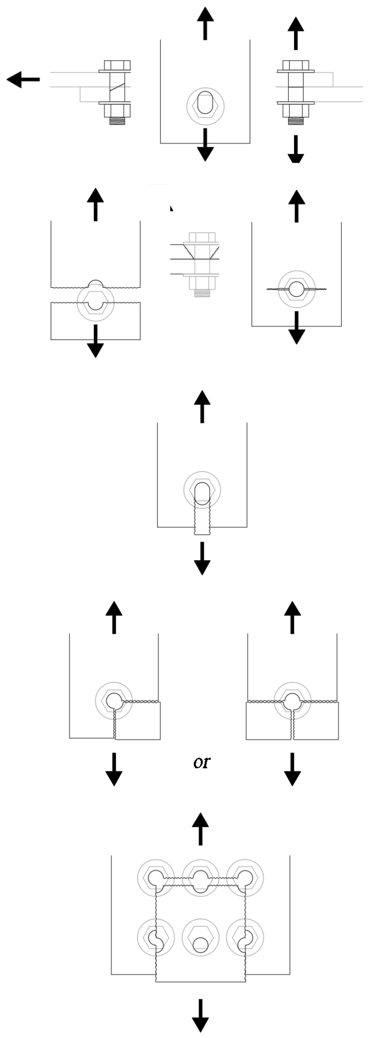
08/2020 – 05/2023: Ph.D. in Civil Engineering – Specialization in structural applications of pultruded FRP

08/2018 – 08/2020: M.S. in Civil Engineering – Specialization in seismic risk assessment of medieval unreinforced masonry religious buildings

09/2012 – 03/2018: B.S. + M.S. in Architectural Engineering - Specialization in seismic design and structural rehabilitation


DESIGN
Design basis
Material behavior
Member behavior
Connection design
Structural system
Strength reduction factors and reliability analysis
Orthotropic material properties and angle dependency
Semi-rigid connections: test, design equations, and parametric study
ASCE 74 (Future versions)
ASCE

Strength Reduction Factors and Reliability Analysis



Bearing limit state

Bolt limit state

Net tension limit state

Pull-through limit state

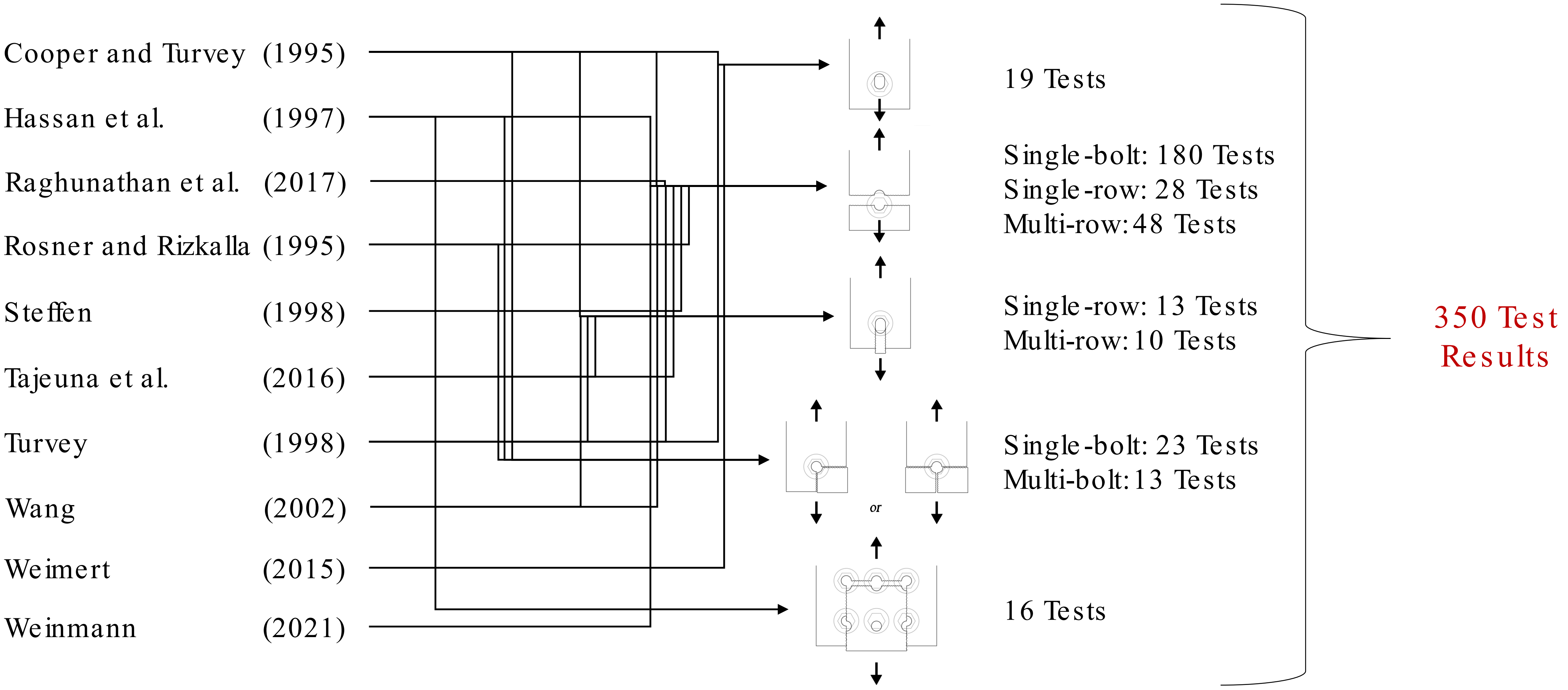
Net tension “splitting” limit state

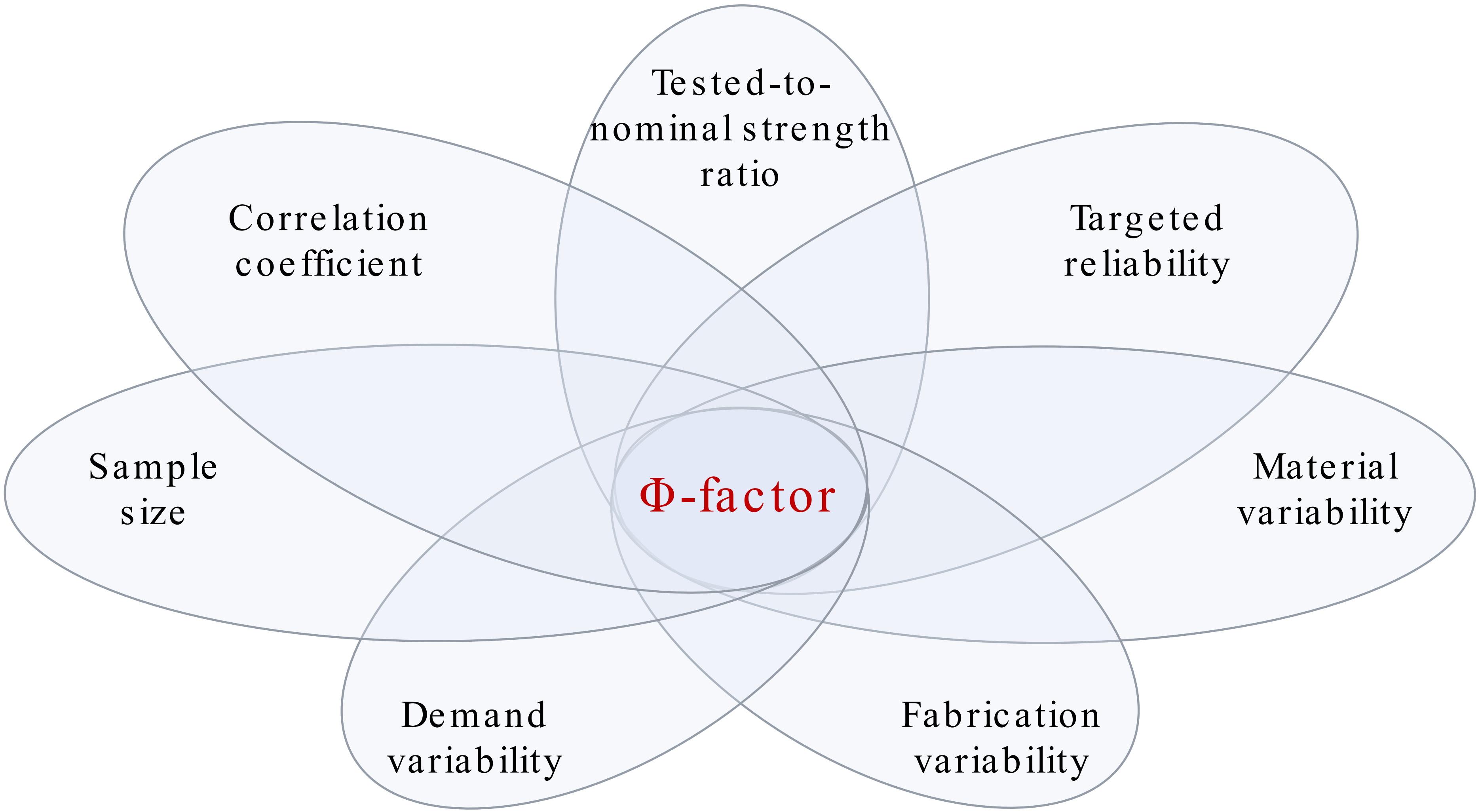
Shear out limit state

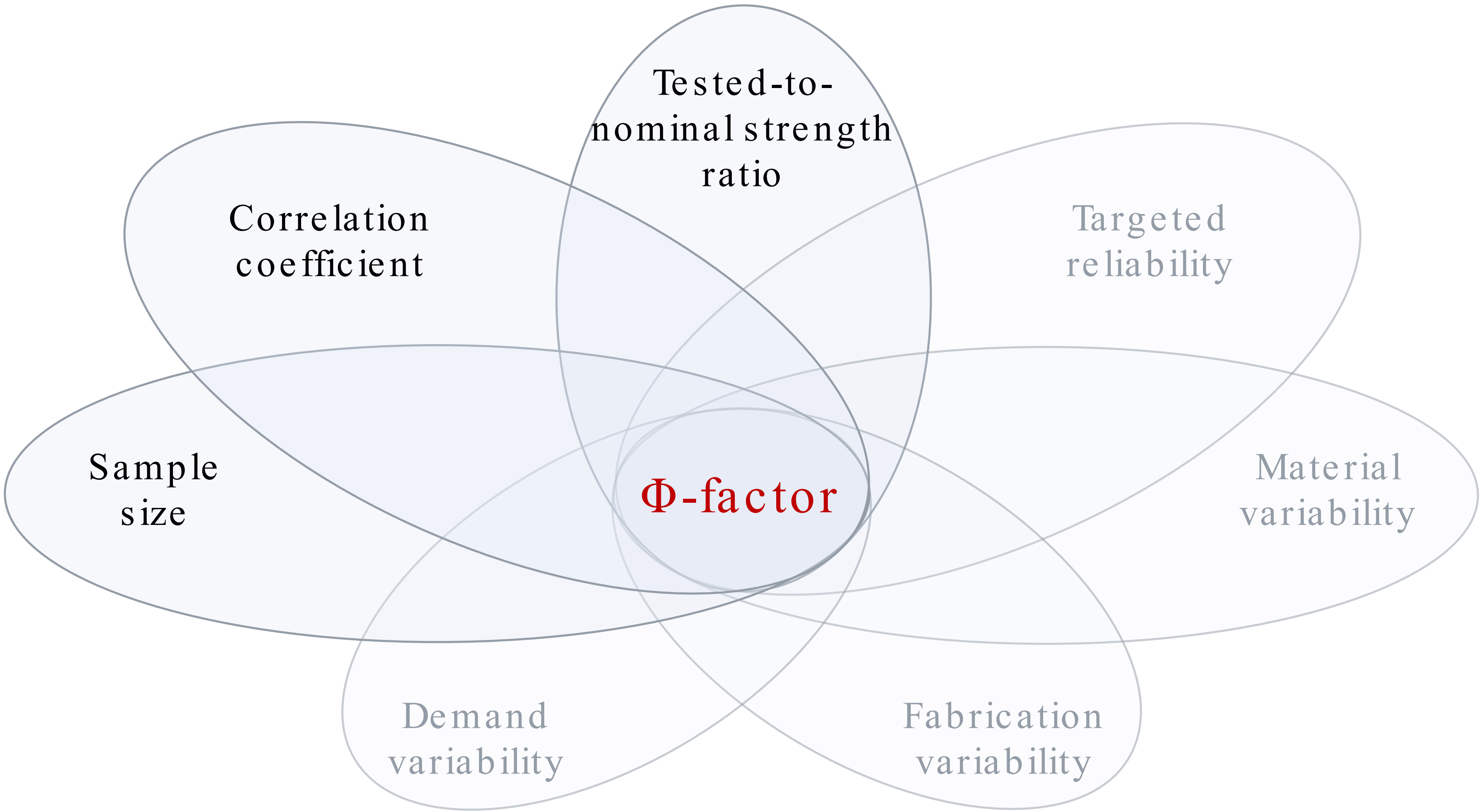
Cleavage limit state

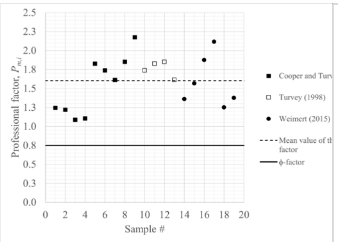
Block shear limit state

Limit state	Φ-factor ASCE/SEI 74
Bearing	0.60
Net tension for one bolt in one row	0.45
Net tension for multiple bolts in one row	0.45
Net tension for multiple rows of bolts	0.45 – 0.50
Shear out for one row of bolts	0.50
Shear out for multiple rows of bolts	0.45
Cleavage for one bolt in one row	0.50
Cleavage for multiple bolts in one row	0.50
Block shear	0.45

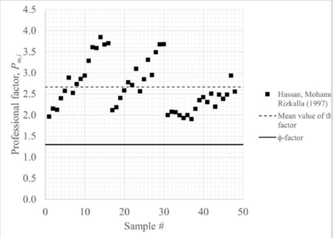

Cooper and Turvey (1995)
Hassan et al. (1997)
Raghunathan et al. (2017)
Rosner and Rizkalla (1995)
Steffen (1998)
Tajeuna et al. (2016)
Turvey (1998)
Wang (2002)
Weimert (2015)
Weinmann (2021)
19 Tests
Single-bolt: 180 Tests
Single-row: 28 Tests
Multi-row: 48 Tests
Single-row: 13 Tests
Multi-row: 10 Tests
Single-bolt: 23 Tests
Multi-bolt: 13 Tests
or
16 Tests
350 Test Results


Tested-to-nominal strength ratio
Correlation coefficient
Targeted reliability
Sample size
Φ-factor
Material variability
Demand variability
Fabrication variability

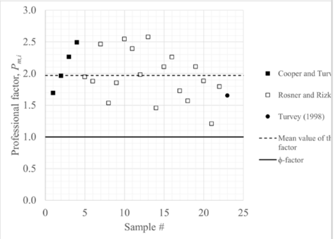

Tested-to-
nominal strength
ratio
Correlation
coefficient
Targeted
reliability
Sample
size
Φ-factor
Material
variability
Demand
variability
Fabrication
variability



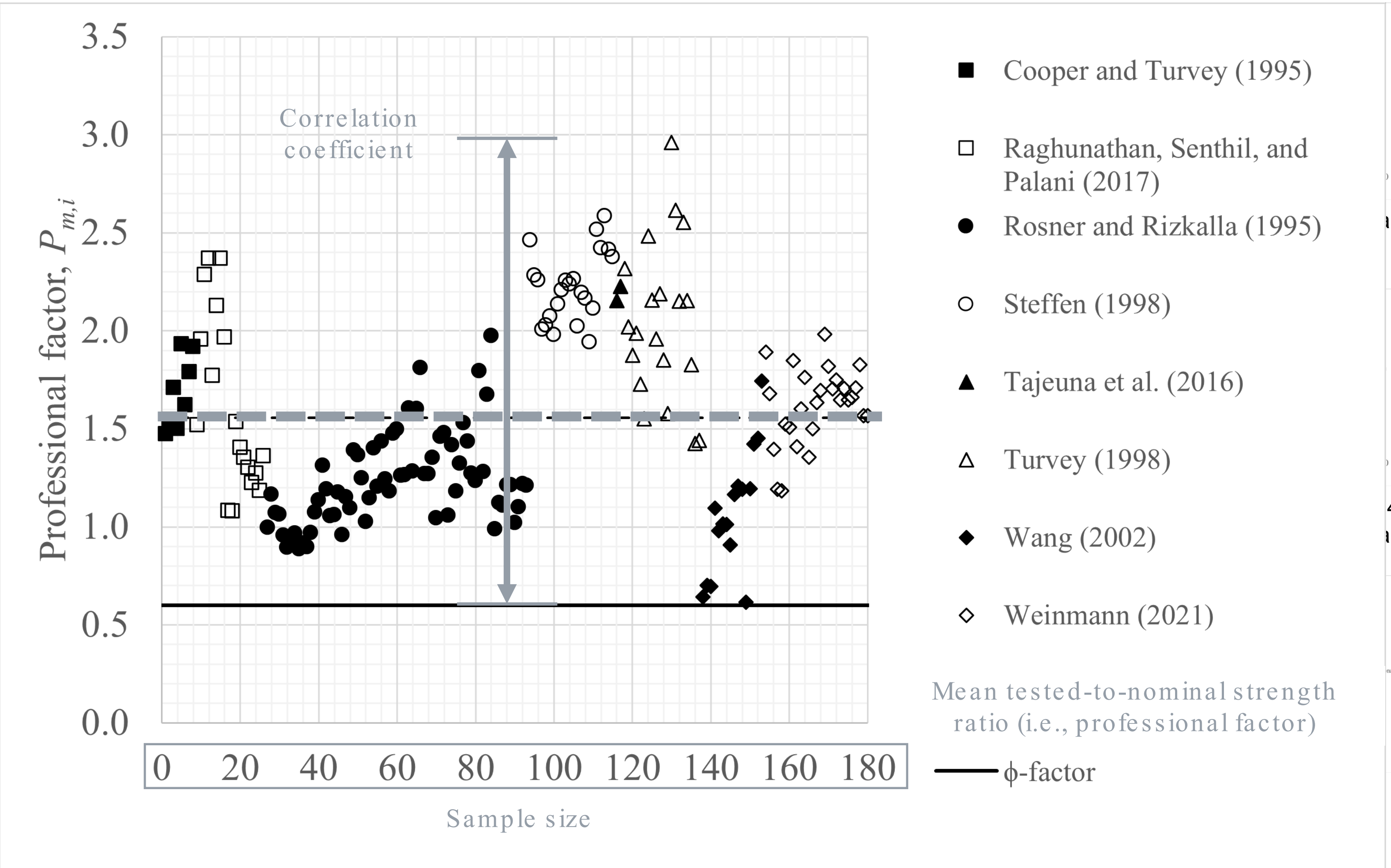
ASCE/SEI 74 &
Pre-Standard

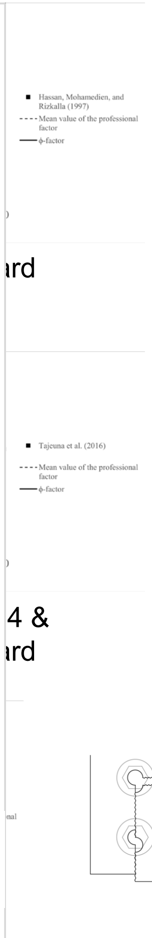


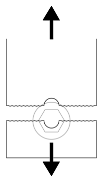
ASCE/SEI 74

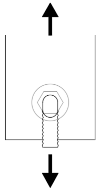


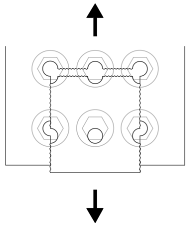
ASCE/SEI 74 &
Pre-Standard

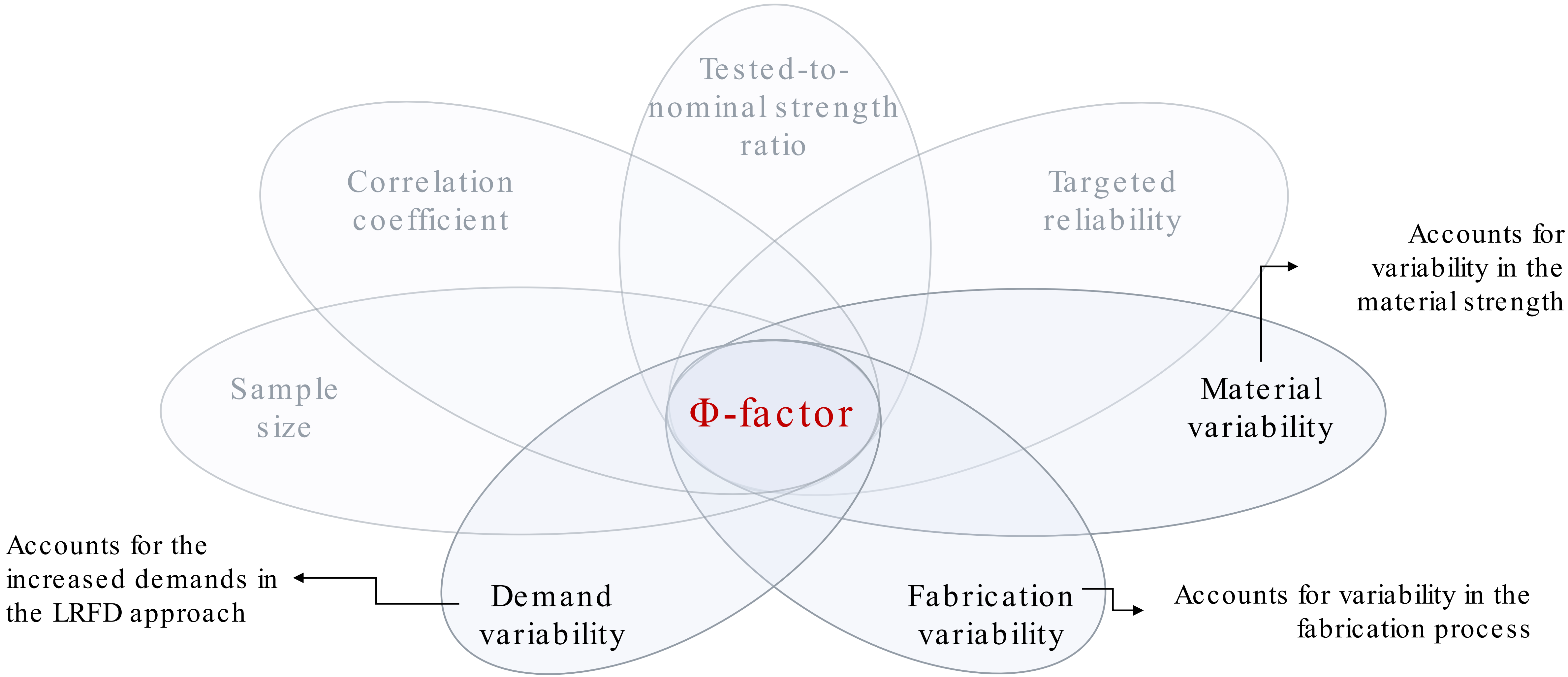


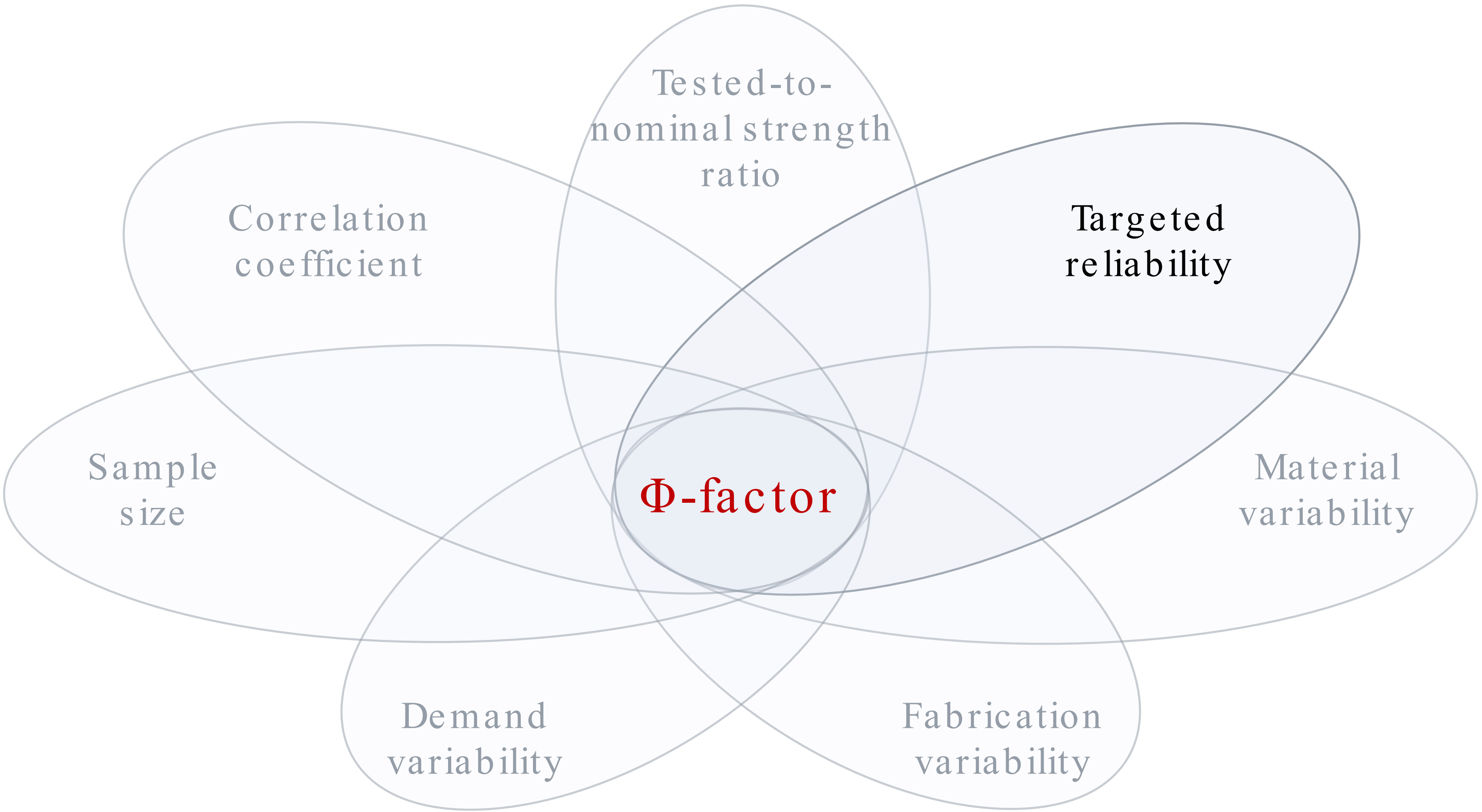


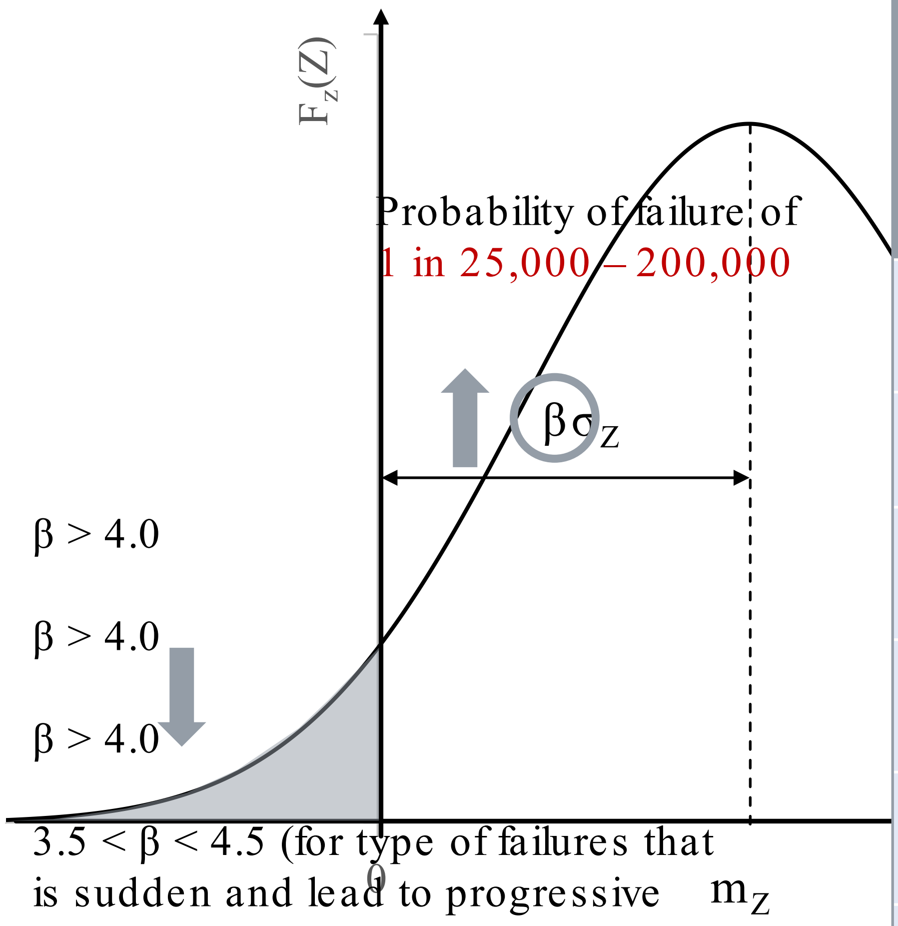






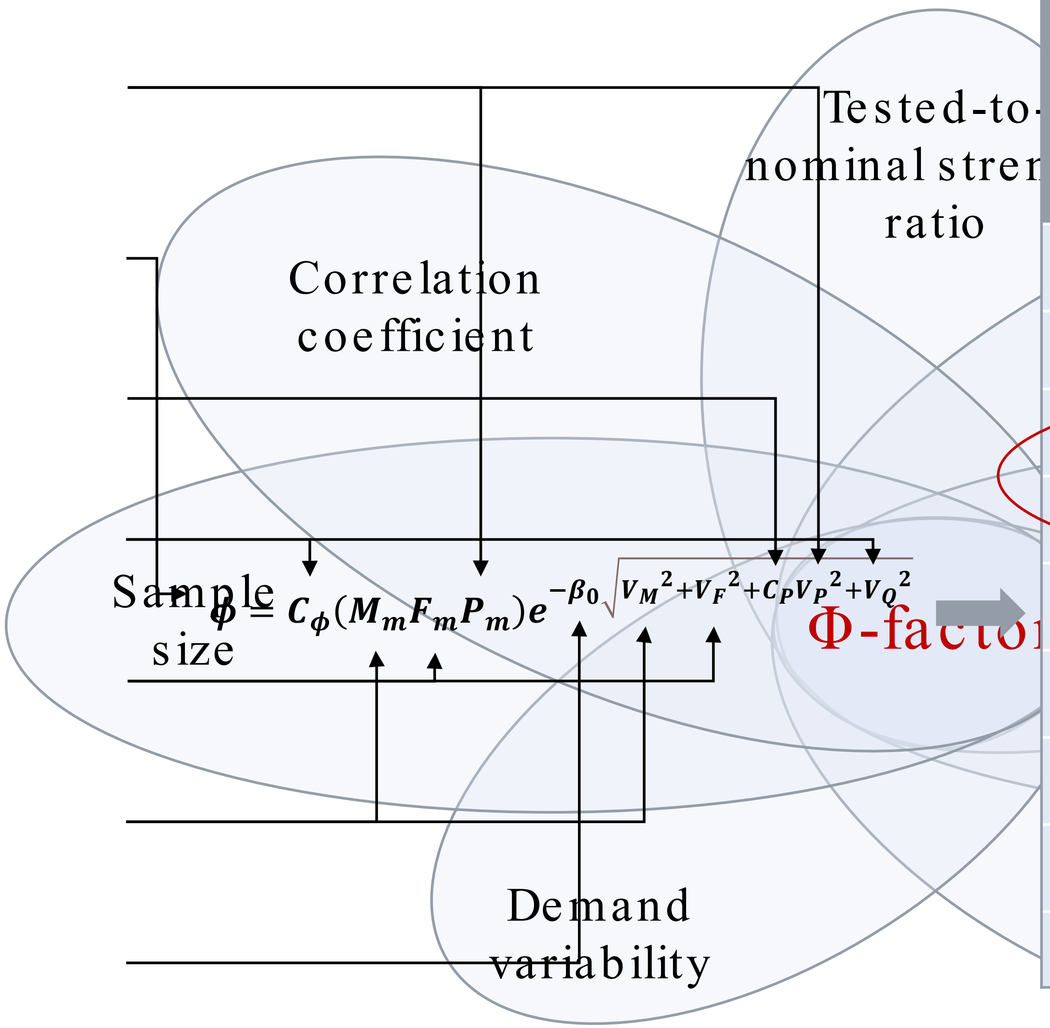

Tested-to-nominal strength ratio
Correlation coefficient
Targeted reliability
Accounts for variability in the material strength
Sample size
Φ-factor
Material variability
Accounts for the increased demands in the LRFD approach
Demand variability
Fabrication variability
Accounts for variability in the fabrication process


Tested-to-nominal strength ratio
Correlation coefficient
Targeted reliability
Sample size
Φ-factor
Material variability
Demand variability
Fabrication variability



- ASCE/SEI 74: β > 4.0
- Pre-Standard: β > 4.0
- Ellingwood: β > 4.0
- ASCE 7-22: 3.5 < β < 4.5 (for type of failures that is sudden and lead to progressive collapse)

Reliability index, β	Probability of failure in a 50-year reference period
0.0	50.0%
2.5	0.60% – 0.63%
3.0	0.10% – 0.15%
3.5	0.02% – 0.03%
4.0	0.003% – 0.004%
4.5	0.0003% – 0.0005%

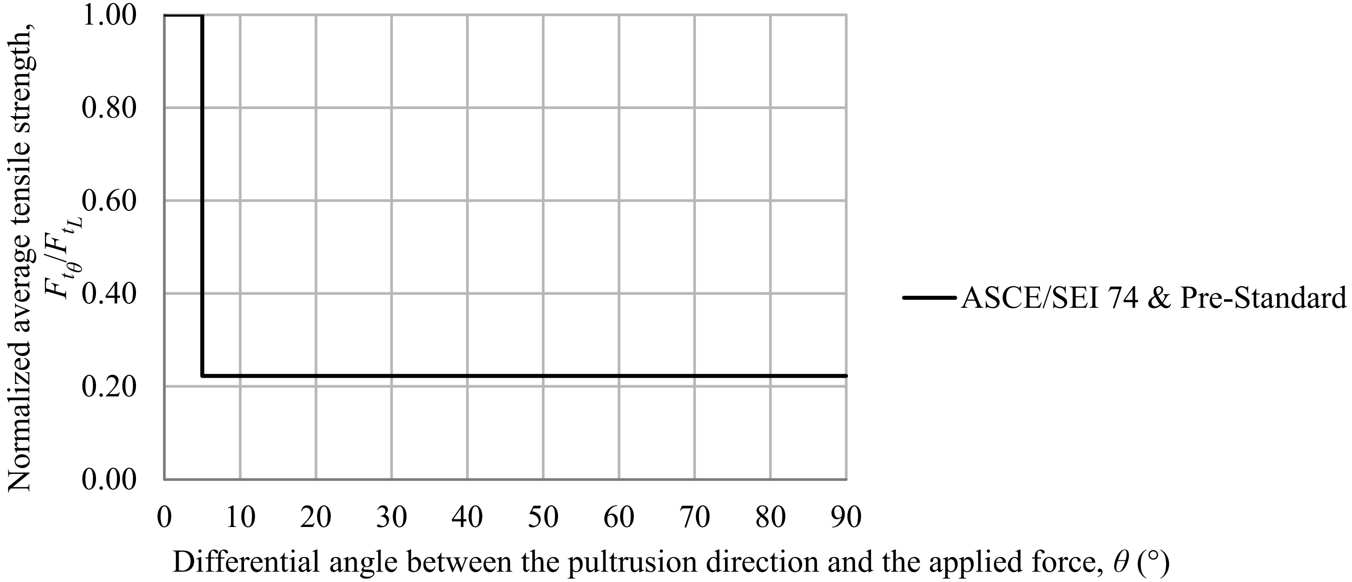


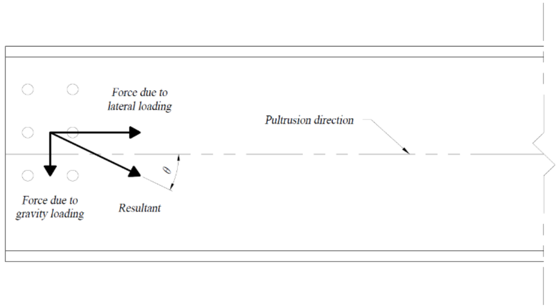
Limit state	Φ-factor	
	ASCE/SEI 74	
	Pirchio et al.	**Current**
Bearing	0.70	0.60
Net tension for one bolt in one row	0.60	0.45
Net tension for multiple bolts in one row	1.50	0.45
Net tension for multiple rows of bolts	1.30	0.45 – 0.50
Shear out for one row of bolts	0.35*	0.50
Shear out for multiple rows of bolts	0.60	0.45
Cleavage for one bolt in one row	1.00	0.50
Cleavage for multiple bolts in one row	2.00	0.50
Block shear	0.75	0.45

* Φ = 0.50 if single shear lap factor equal 0.80 is considered.

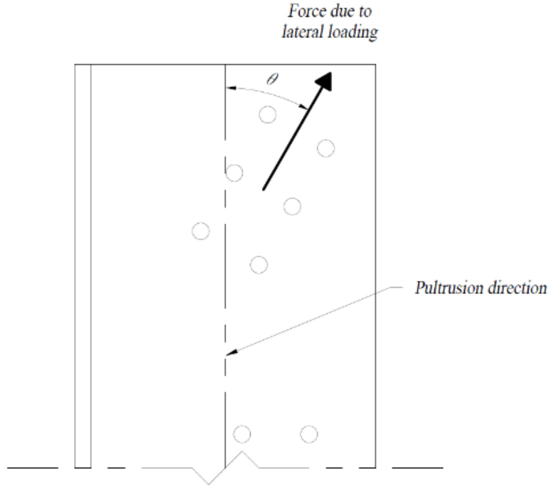
Orthotropic Material Properties and Angle Dependency

Lower-bound specified mechanical properties	ASCE/SEI 74	Manufacturer A	Manufacturer B
Longitudinal tensile strength	210 MPa	210 MPa	210 MPa
Transverse tensile strength	50 MPa	50 MPa	50 MPa
Longitudinal tensile modulus	21,000 MPa	17,200 MPa	17,200 MPa
Transverse tensile modulus	5,500 MPa	5,500 MPa	5,500 MPa





Collector beam



Braced connection

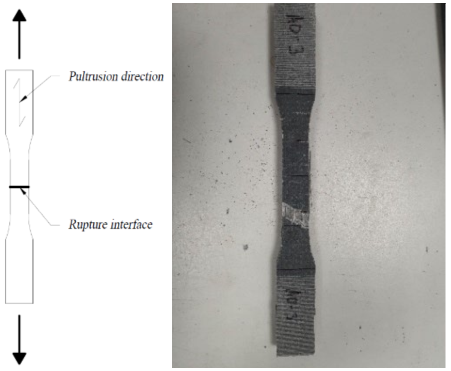
Test standard: ASTM D638

Specimen tested: Wishbone coupons

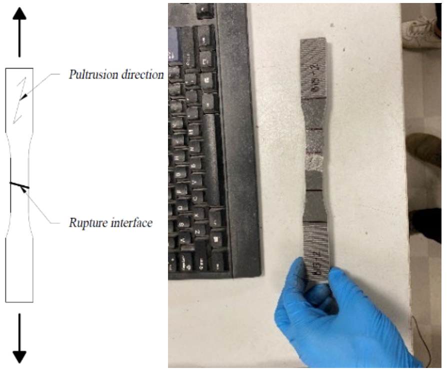
Specimen properties: 2” gage
Extracted from different members
Cut at different angles
Thickness 3/8” – 1/2”

Sample size:
94 at 0º
21 at 10º
7 at 15º
21 at 20º
34 at 30º
24 at 45º
2 at 60º
25 at 90º

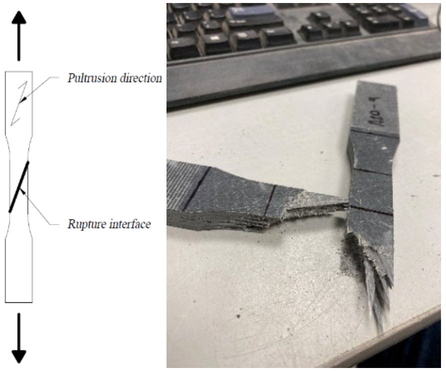
228 specimens tested



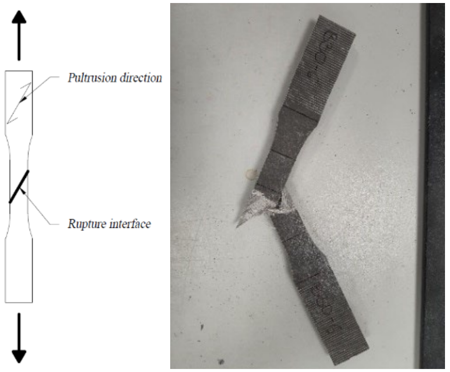
θ = 0°



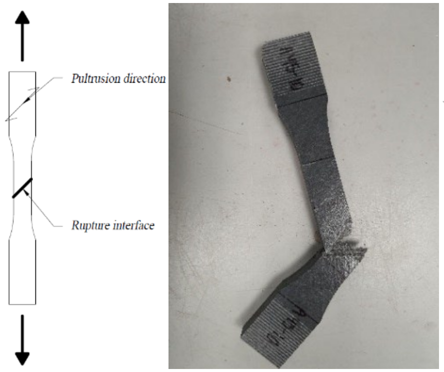
θ = 15°



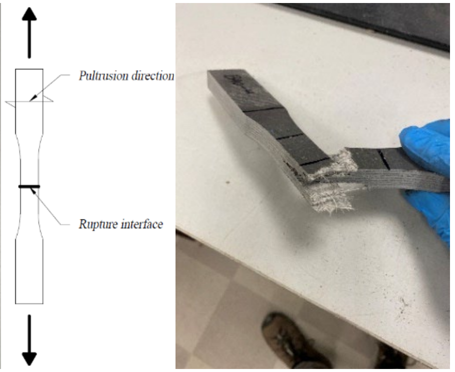
θ = 20°



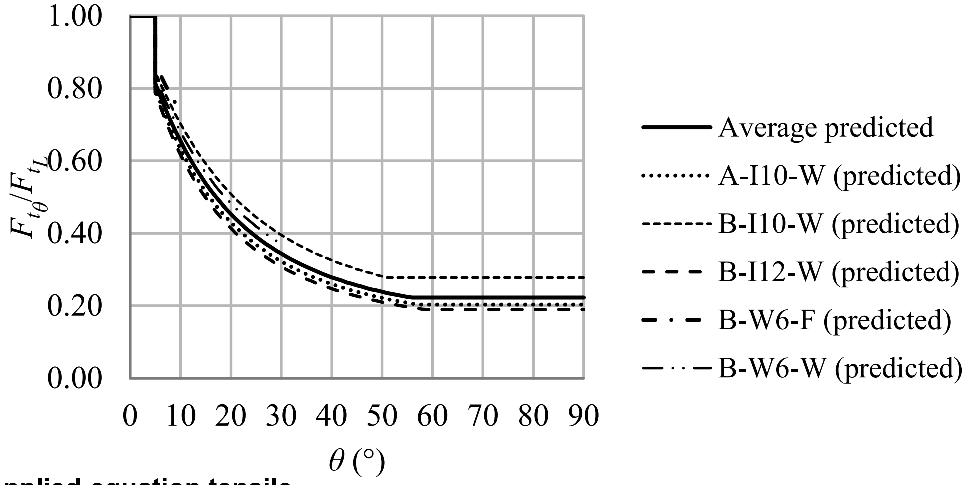
θ = 30°



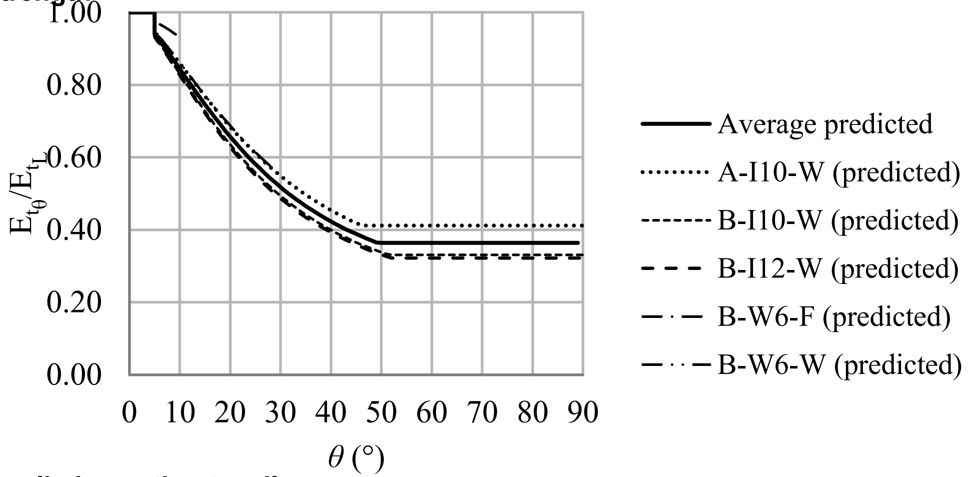
θ = 45°



θ = 90°



Applied equation tensile strength



Applied equation tensile modulus

Hankinson's and NDS equation (1921)

Proposed Equation

$$x^{\theta} = \frac{x^L x^T}{x^L (\sin\theta)^2 + X^T (\cos\theta)^2}$$

$$x^{\theta} = \frac{x^L x^T}{x^L (\sin\theta)^{\alpha} + X^T (\cos\theta)^{\beta}} \geq x^T$$

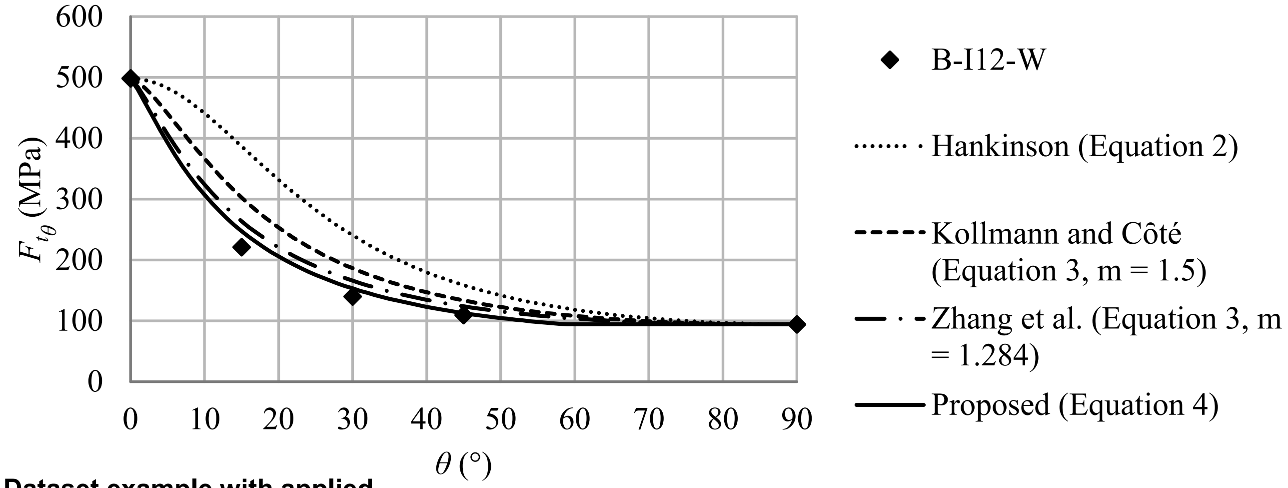
x^{θ} = Generic material property depending on the angle, θ

x^L = Generic longitudinal material property

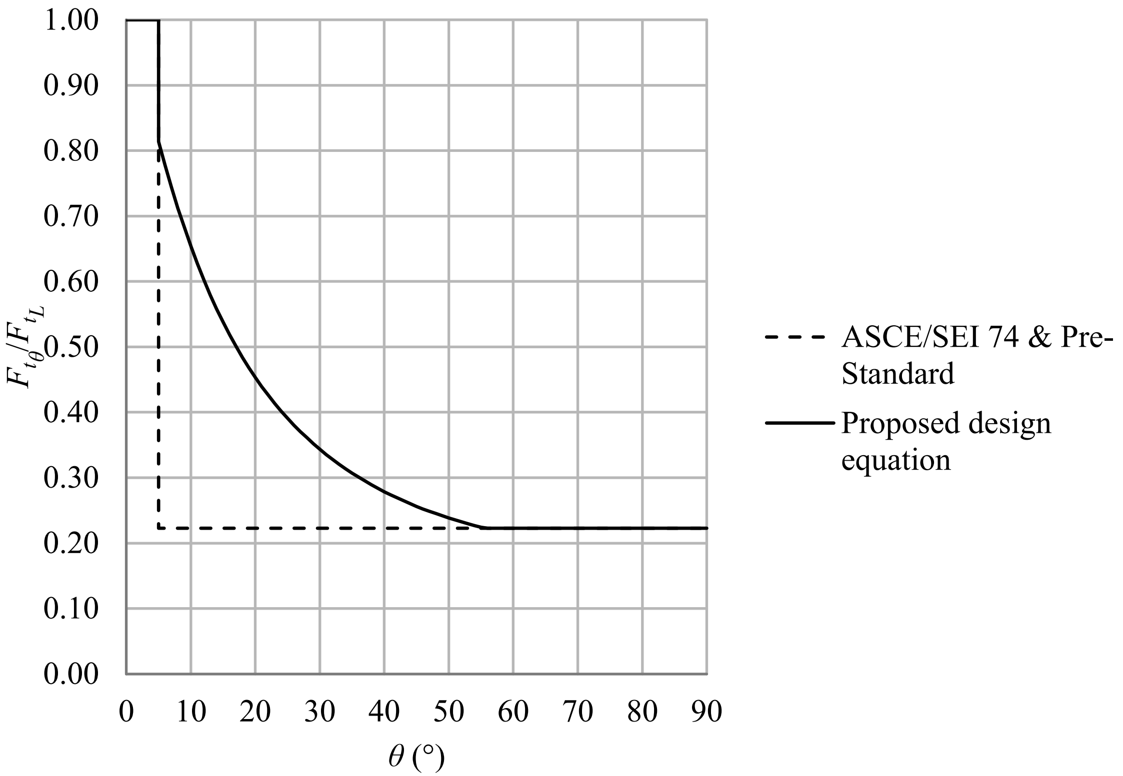
x^T = Generic transverse material property

$\alpha = 1.22$ (strength) or 1.54 (modulus)

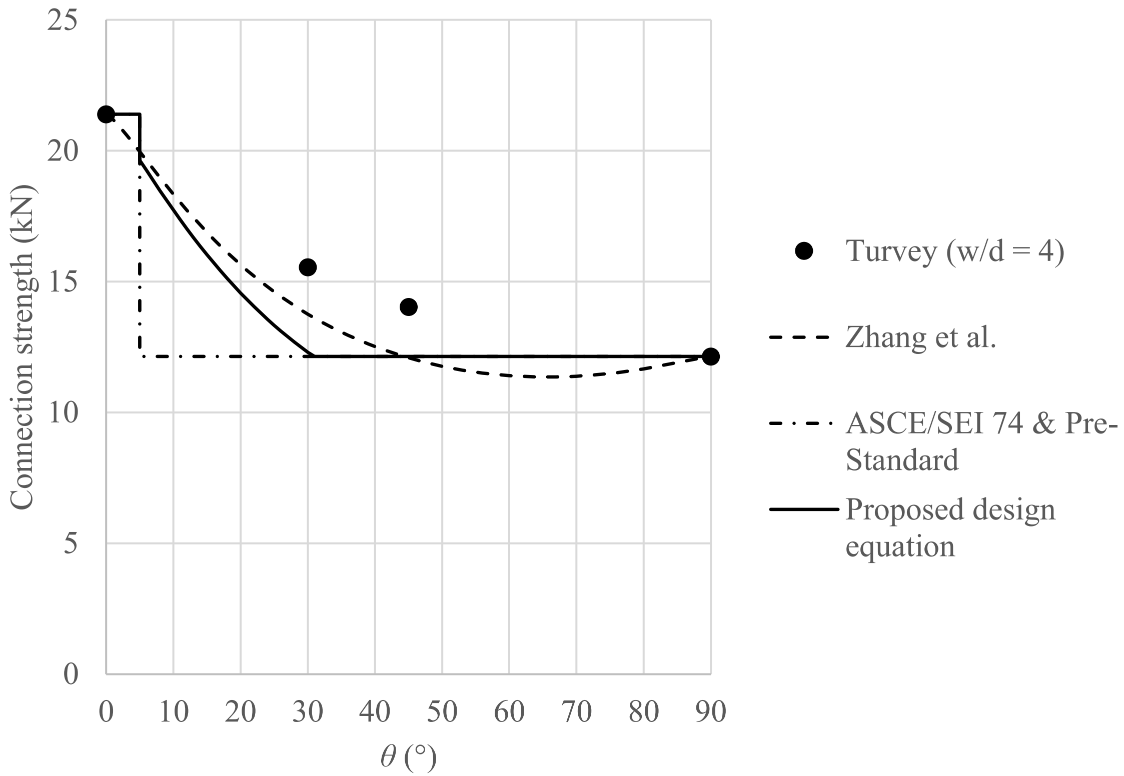
$\beta = 0.12$ (strength) or 0.11 (modulus)



Dataset example with applied equations



Material strength



Connection strength for case study connection

Semi-Rigid Connections

Test, Design Equations, and Parametric Study

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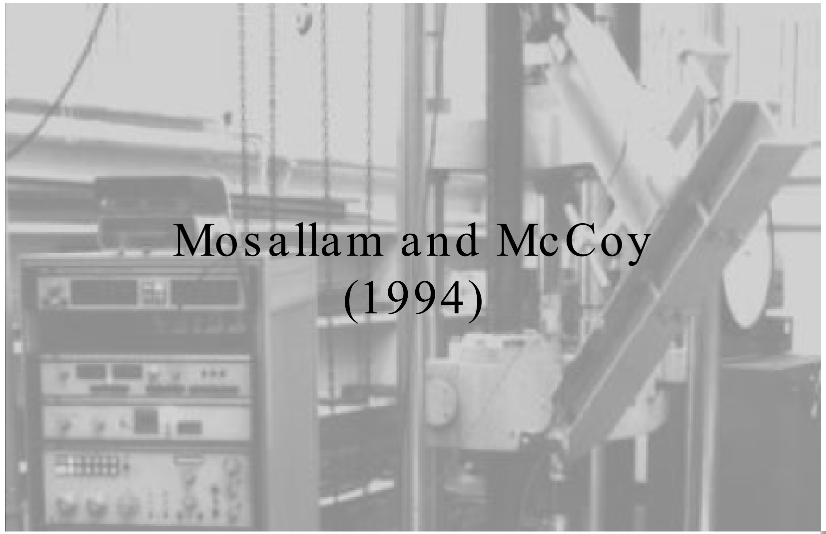
- Limited structural application of the results due to the size of the tested members
- High cost of the proposed configurations due to the large number of connectors utilized
- Inapplicability to single-story platforms due to the interaction of the clip on the top flange with the deck
- Limited sample size of the test conducted (i.e., no defined nor defined design strength reduction)
- Low efficiency of the connections due to configurations borrowed from steel connections that engage weak material properties of pultruded FRP



Mosallam and McCoy (1994)

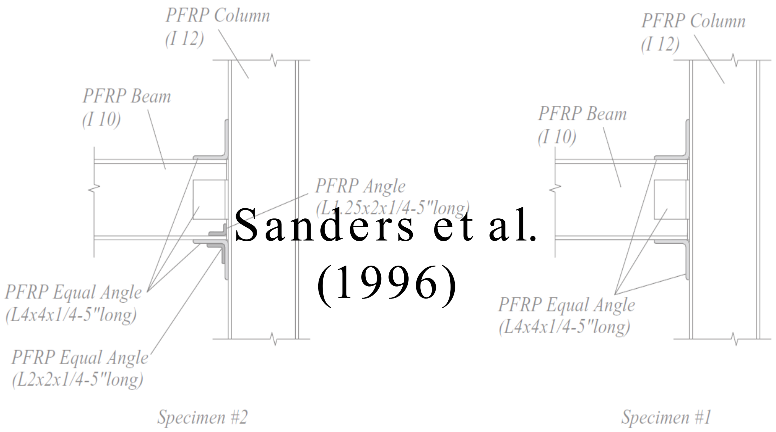
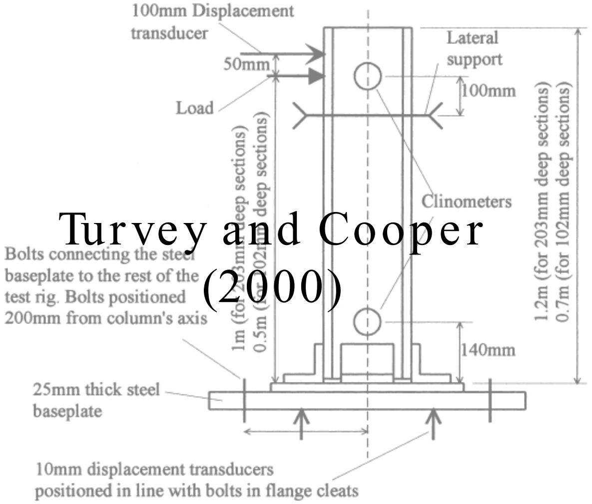
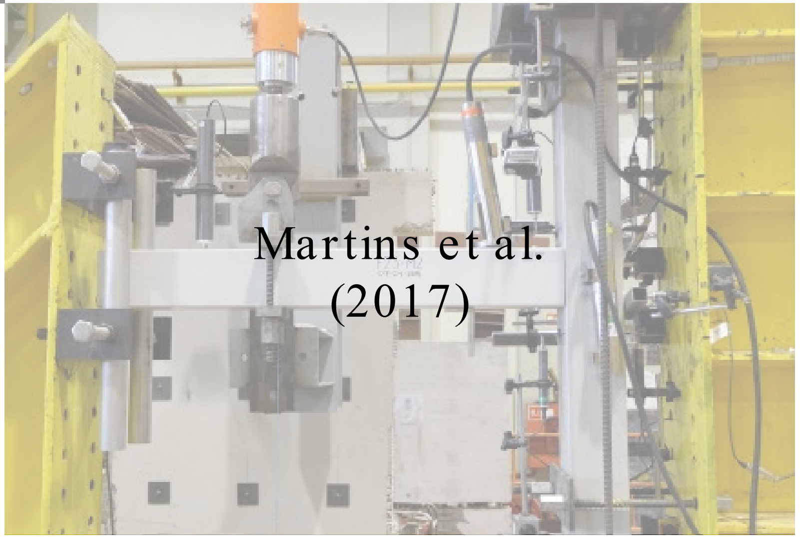


Figure 7-101. Beam-to-column bonded specimens details.
Source: Sanders et al. (1996).

Sanders et al. (1996)

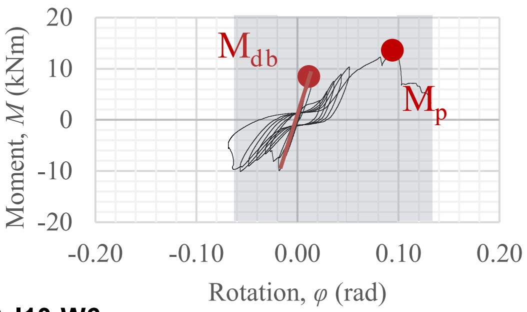


Turvey and Cooper (2000)

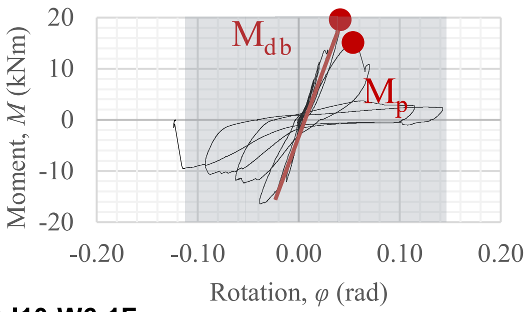


Martins et al. (2017)

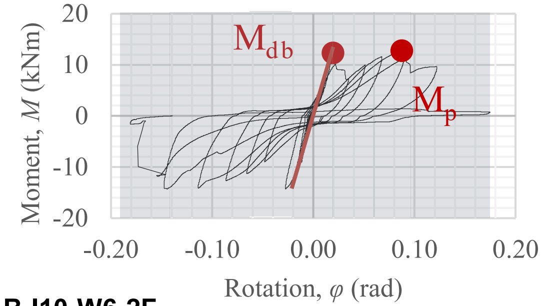
Beam: I10x5x1/2 (1,137 mm)	Beam: I10x5x1/2 (813 mm)	Beam: I10x5x1/2 (813 mm)	Beam: I12x6x1/2 (864 mm)	Beam: I12x6x1/2 (1,372 mm)
Column: W6x3/8 (635 mm)	Column: W6x3/8 (457 mm)	Column: W6x3/8 (457 mm)	Column: W8x1/2 (508 mm)	Column: W8x1/2 (762 mm)
Adhered surfaces: Non-abraded	Adhered surface: Abraded	Adhered surfaces: Abraded	Adhered surfaces: Abraded	Adhered surfaces: Abraded
Samples: 12	Samples: 12	Samples: 12	Samples: 10	Samples: 5
ID: A-I10-W6	ID: B-I10-W6-1F	ID: B-I10-W6-2F	ID: B-I12-W-S	ID: B-I12-W-L



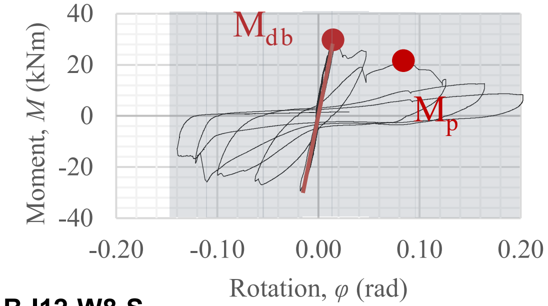
A-I10-W6



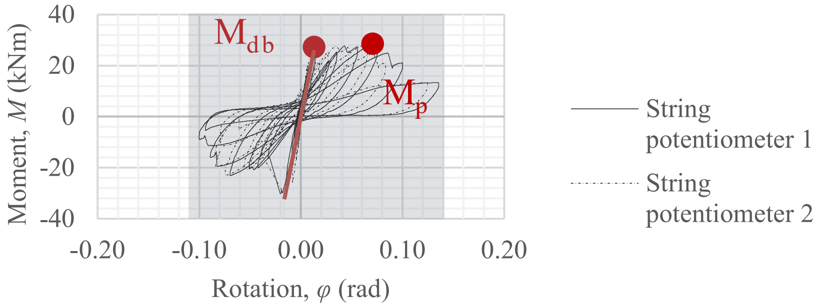
B-I10-W6-1F



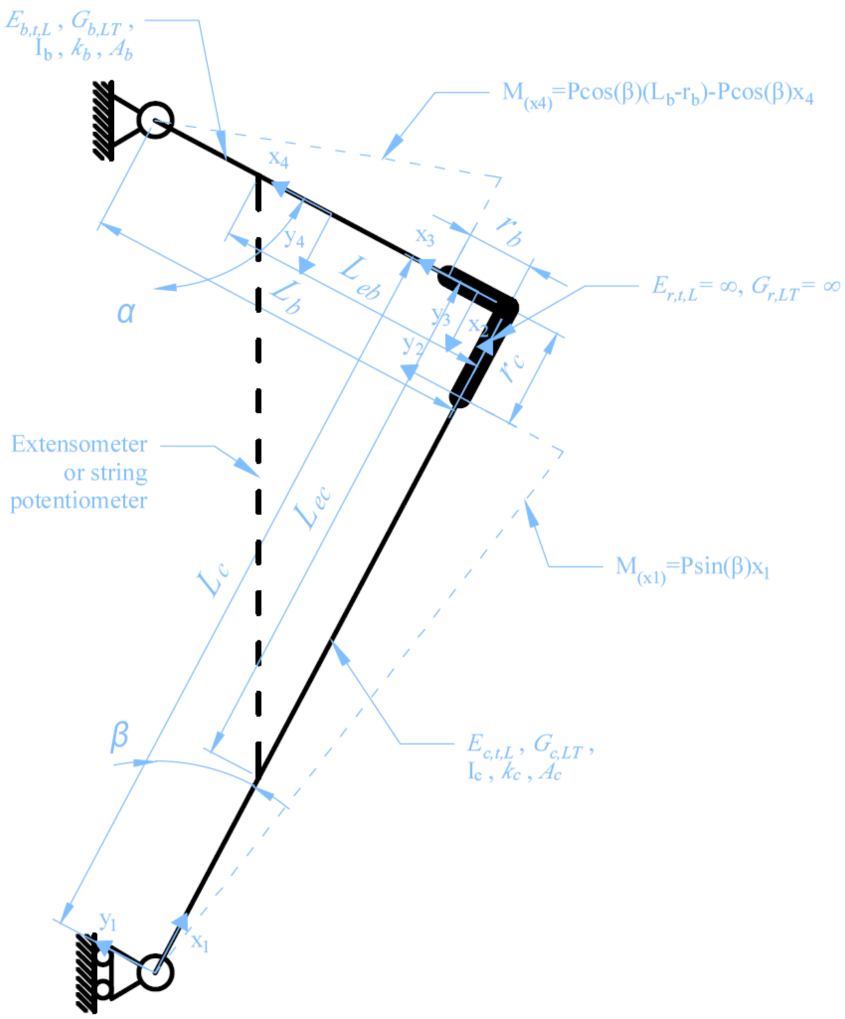
B-I10-W6-2F



B-I12-W8-S



B-I12-W8-L



$$\varphi = \varphi_c + \varphi_{e,d}$$

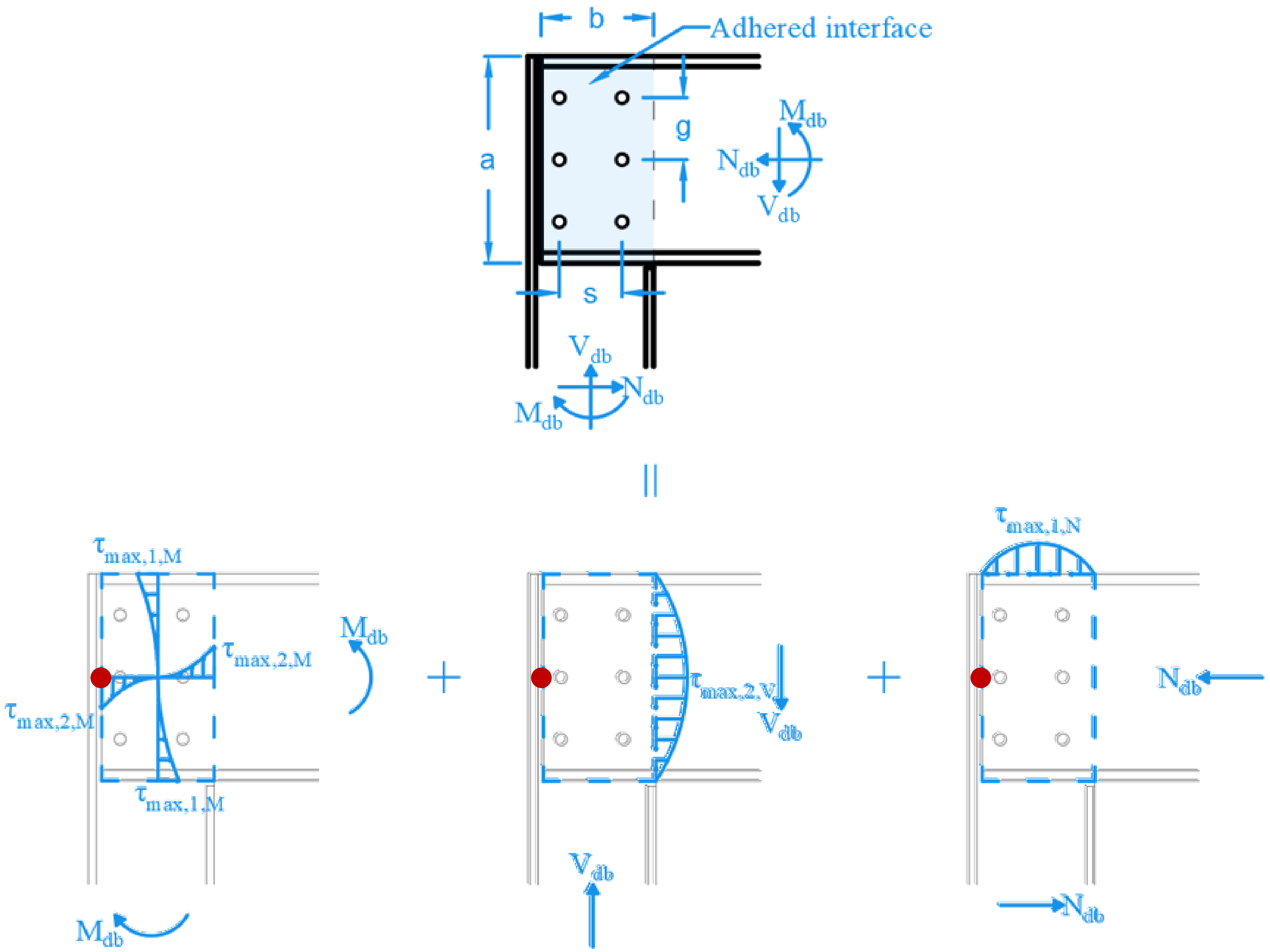
$$\varphi = \frac{P \sin\beta\, L_c}{k_r}$$

$$\varphi_c = \frac{P \sin\beta\, L_c}{K_r}$$

$$\varphi_{e,d} = \frac{y_{(x_3=0)} - y_{(x_4=L_{e,b}-r_b)}}{L_{e,b}} - \frac{y_{(x_1=L_c-L_{e,c})}}{L_{e,c}}$$

$$\boldsymbol{K_r = \left(\frac{1}{k_r} - \frac{\varphi_{e,d}}{P \sin\beta\, L_c}\right)^{-1}}$$

Type	k_r (kNm/rad)	K_r (kNm)	K_r / k_r
A-I10-W6	519	970	1.83
B-I10-W6-1F	785	1,227	1.74
B-I10-W6-2F	670	1,275	1.82
B-I12-W8-S	1,617	3,167	2.02
B-I12-W8-L	1,993 – 2,880	3,912 – 3,250	1.95 – 1.12



$$\tau_{max,2} = \tau_n = \tau_{max,2,M} + \tau_{max,2,V} + \tau_{max,2,N}$$

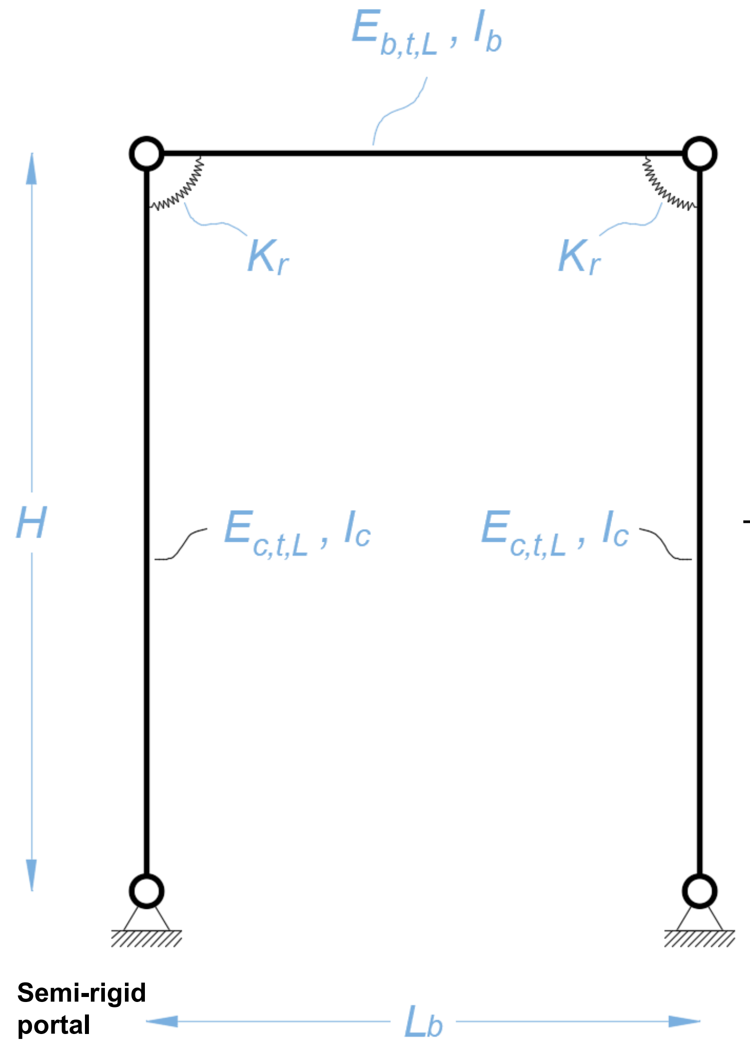
$$\tau_{max,2,M} = M_{db}\frac{b}{J_{t,net}}$$

$$\tau_{max,2,V} = 1.5\frac{V_{db}}{A_{net}}$$

$$\tau_{max,2,V} = 0$$

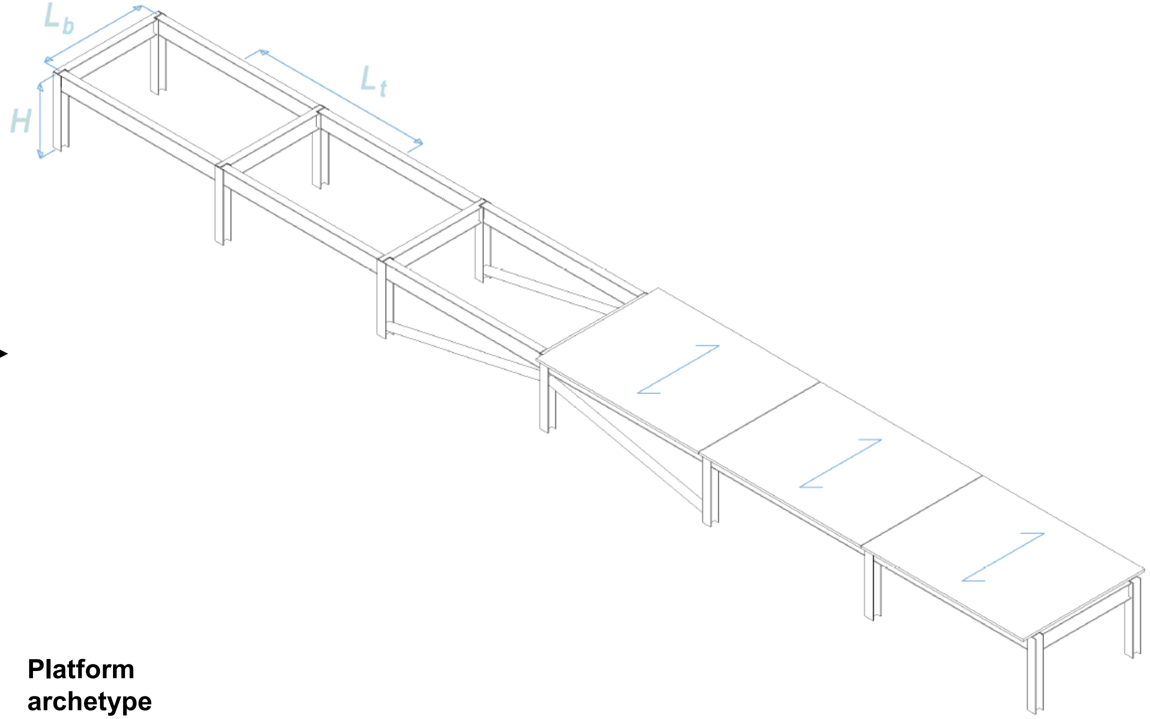
$$\boldsymbol{M_{db} = \left(\tau_n - 1.5\frac{V_{bd}}{A_{net}}\right)\frac{J_{t,net}}{b}}$$

$\boldsymbol{\phi = 0.60}$ (A-I10-W6 included) or $\boldsymbol{\phi = 0.80}$ (A-I10-W6 excluded)

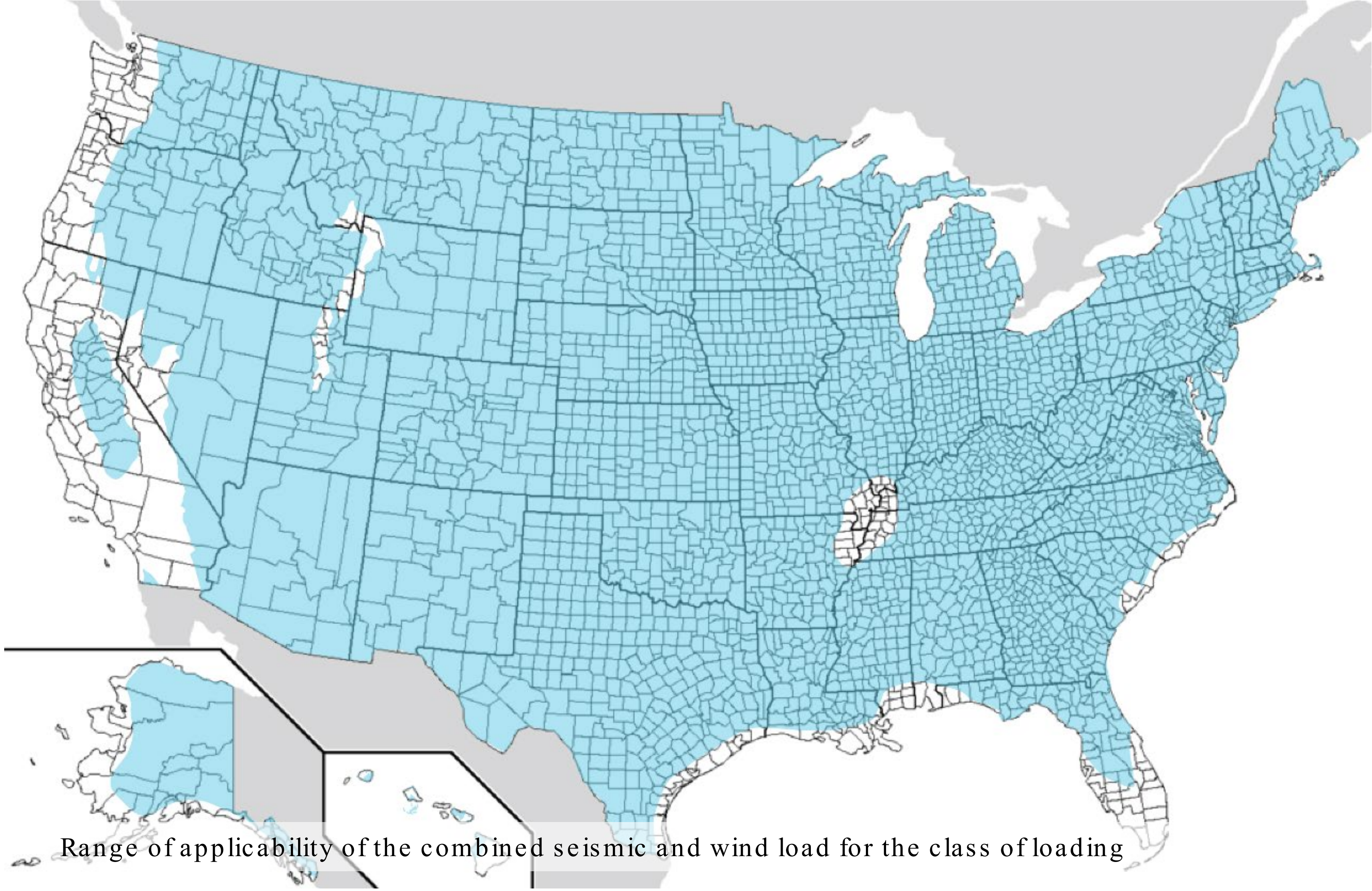


Semi-rigid portal

$$k = \frac{6E_{c,t_L}I_c}{H^3}\left(\frac{2\alpha_s}{2\alpha_s + \beta_s + \frac{6\alpha_s E_{c,t_L}I_c}{K_r H}}\right)$$



Platform archetype



Range of applicability of the combined seismic and wind load for the class of loading

Low class of lateral loading

Seismic: $S_s = 0.321g$
$S_1 = 0.083g$
$T_L = 16s$

Wind: V = 49.2 m/s (110 mph)

Moderate class of lateral loading

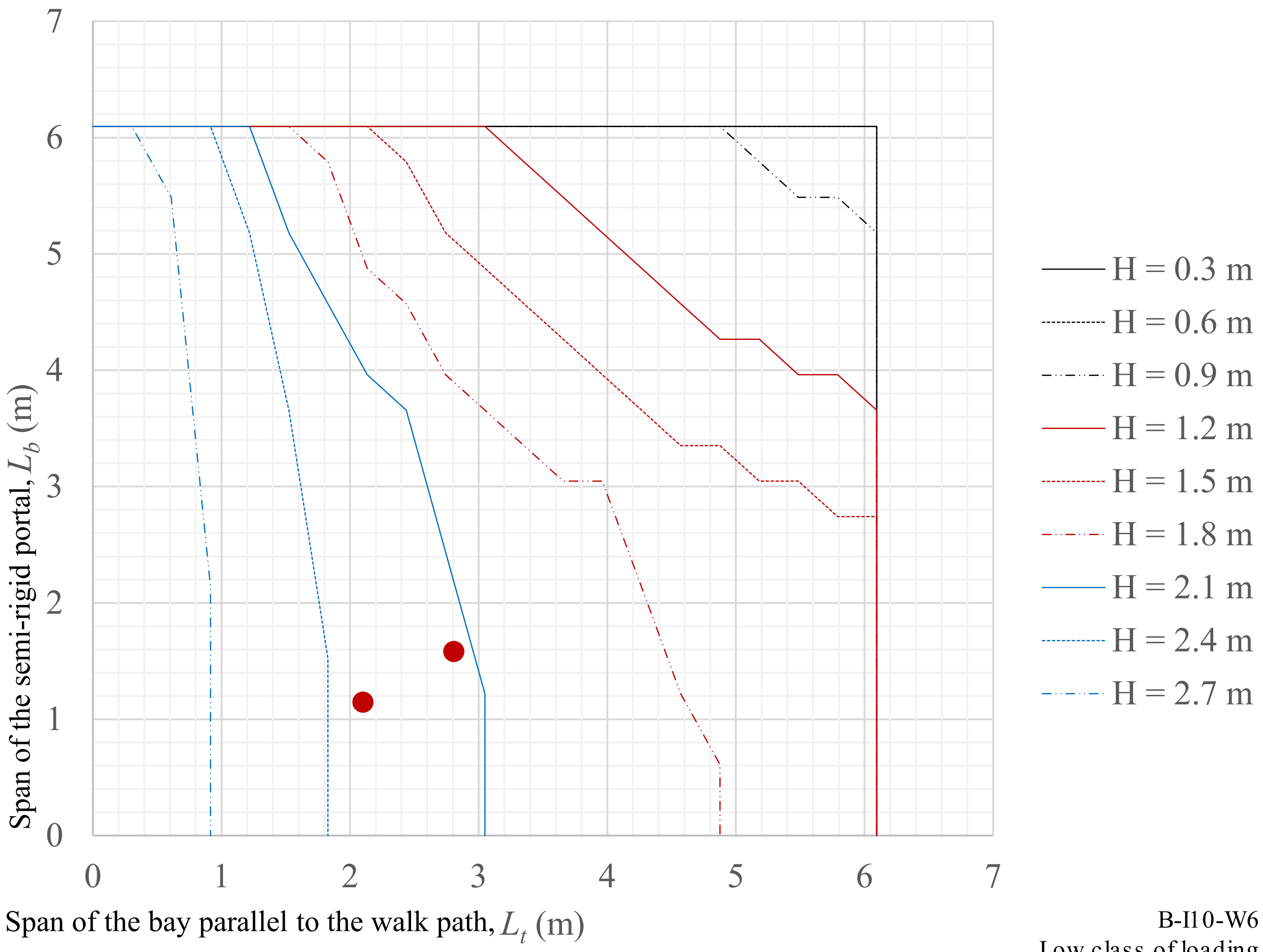
Seismic: $S_s = 0.552g$
$S_1 = 0.128g$
$T_L = 16s$

Wind: V = 53.6 m/s (120 mph)

High class of lateral loading

Seismic: $S_s = 1.500g$
$S_1 = 0.300g$
$T_L = 16s$

Wind: V = 62.6 m/s (140 mph)



B-I10-W6
Low class of loading

Applications

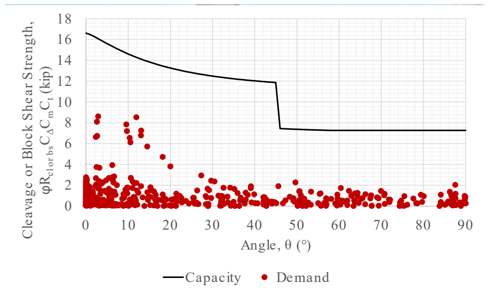
DESIGN

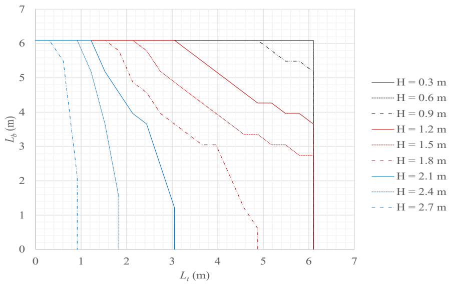
- Design basis
- Material behavior
- Member behavior
- Connection design
- Structural system

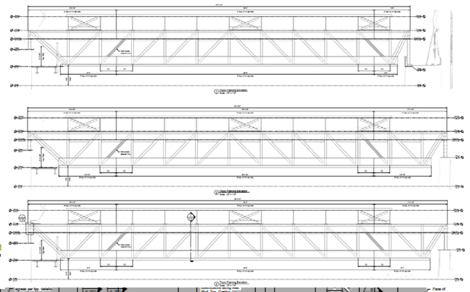
Strength reduction factors and reliability analysis

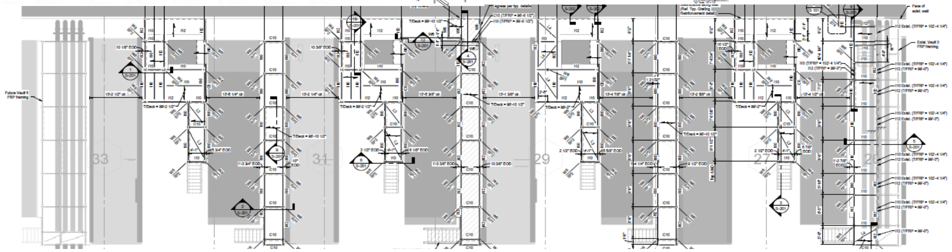
Orthotropic material properties and angle dependency

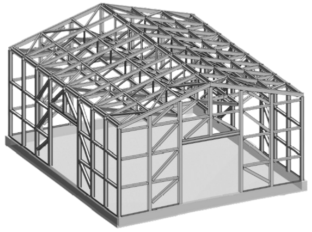
Semi-rigid connections: test, design equations, and parametric study

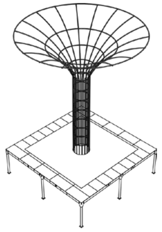












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