UAA College of Engineering
UNIVERSITY of ALASKA ANCHORAGE

Determining Beam Pocket Strength in Structural Insulated Panels (SIPs) using Reliability Targeted Analysis

SEAAK Bi-monthly Meeting

Presented By: Scott Hamel, PE, SE, PhD

July 28, 2021

R-Valued HOMES
Housing

Alaska Insulated Panels

MADE IN ALASKA
Alaskan

Special Thanks to

- Jayci VanDehey, BSCE Student
- John Morton, BSCE Student
- Sean Carlson, BSCE ’21
- Nicholas Schwantes, BSCE ‘21
- Tim Kirk, UAA Research Professional
- Corbin Rowe, UAA Machinist

Topics

Topics Previously Covered

- Code Provisions (2018 and 2019)
- R-Value Tests (2018)
- Compression, Bending, Racking Tests (2018)
- Creep Mechanics and Creep Testing (2019)

Topics for Today

- Introduction – What are SIPs
- Beam Pocket Test Procedure
- Beam Pocket Results
- Reliability Targeted Analysis (RTA)

Topics for Another Day

- SIP Spread Footings
- Foundation Wall Design
- Seismic Analysis and Testing

What is a SIP?

- Structural Insulated Panel (SIP)
  - Provides both the structure and insulation
  - Used for walls, floors, foundation, and roof
- Manufactured “sandwich” composite panel
  - Faces:
    - OSB
    - Plywood
    - Cement Board
    - Metal
    - Fiber-reinforced Polymer (FRP)
  - Core:
    - EPS – Expanded Polystyrene
    - XPS – Extruded Polystyrene
    - PUR – Polyurethane Foam

Characteristics of SIP Insulation

(Cold Climate Housing Research Center, 2015)

Insulation	Approx. R-Value per inch	Water Vapor Permeability (Perm rating of 1 inch)
EPS	3.6	3
XPS	5	1
PUR	6	1

Alaska Insulated Panels (AIP) Plywood-PU SIPs

- 6.5-inch Panels (5.5 inches of foam)
- Higher moisture resistance
  - CDX grade plywood
  - Closed cell polyurethane foam (PU)
- More Durable
- Stiffer, higher strength
- No Adhesive
- Higher R-value (R=40)

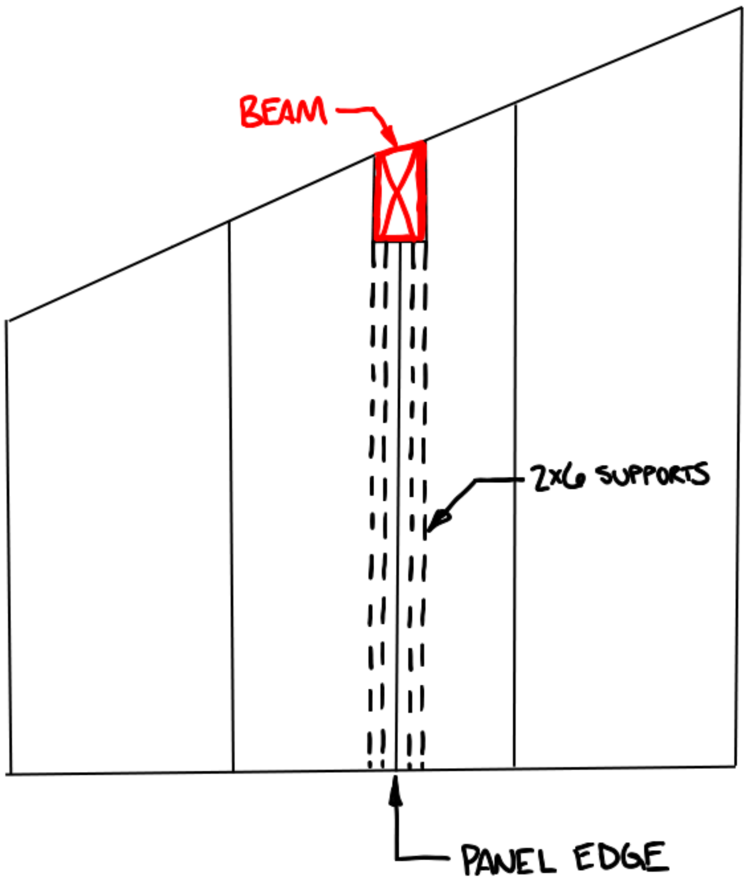
Image Courtesy of Alaskan Insulated Panels

How Are They Made?

- Plywood fastened to 5.5” edge forms
- Placed into 4’x16’ hydraulic press
- Pressure is applied while liquid foam is injected
- Forms removed and panels customized
- 4x8 Ply-PU SIP:
  - ~120 lbs (3.6 psf)
  - Foam = ~2.2 pcf

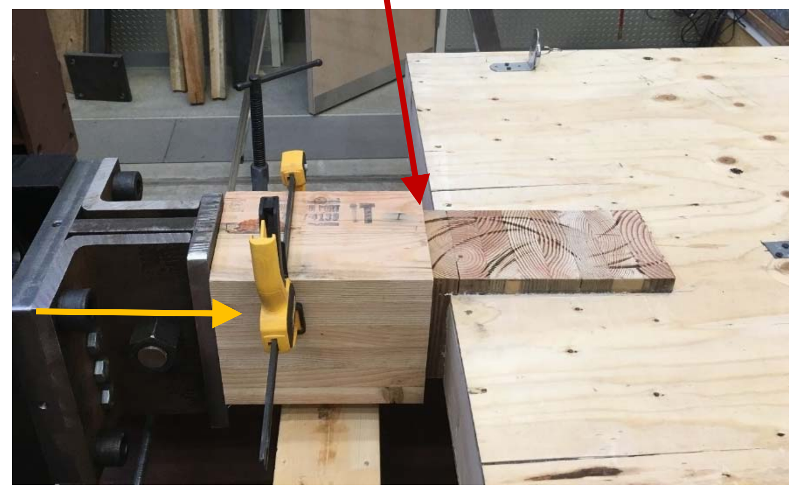
Beam Pocket Testing

Why Beam Pockets?



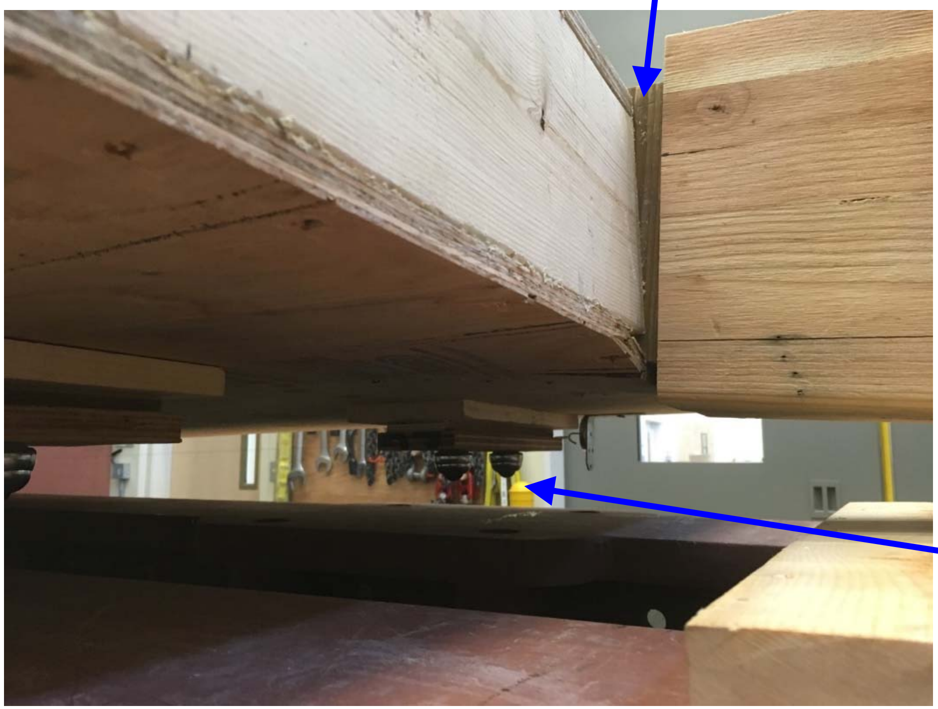
Current Beam Support Process

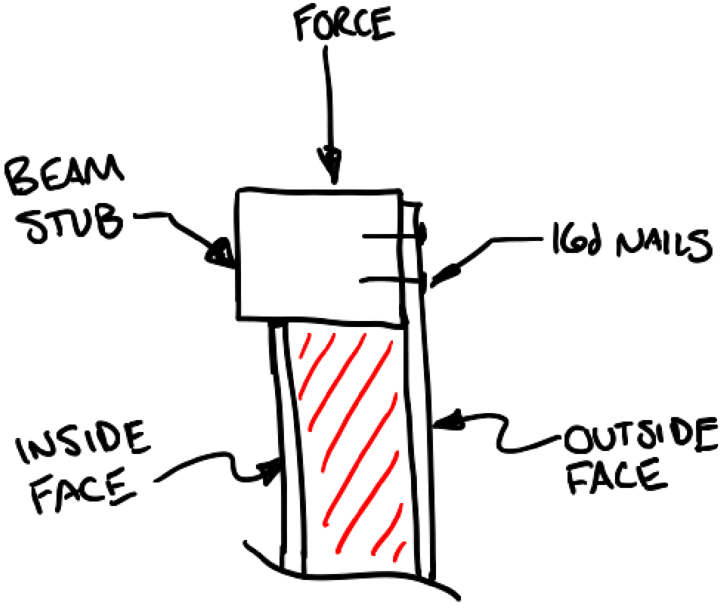
Initial Tests (2018)



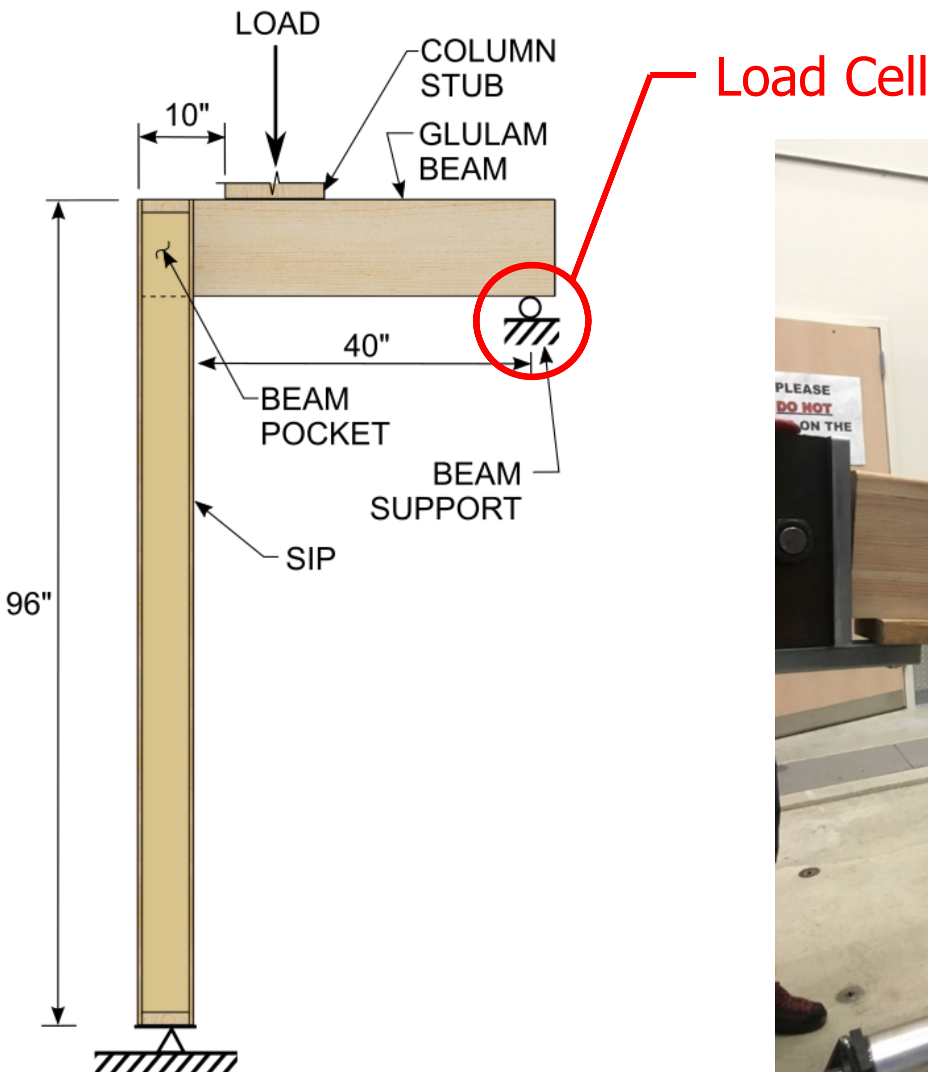
Initial Tests (2018)

- Failure of outside face support
- Rotation of Beam





Phase 1 Test Setup (2019)

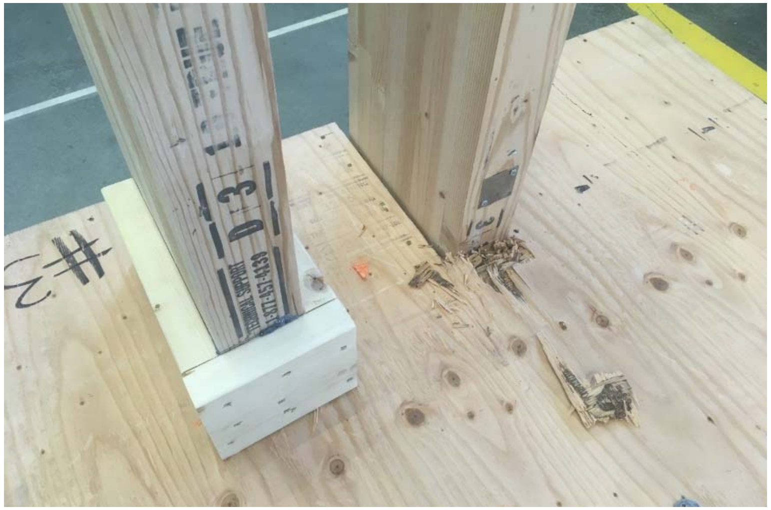


Phase 1 Specimens (2019)

- 10 tests
- 3.5”x12” Beam pockets
- One face of plywood cut
- Pocket Reinforced with 12 gage 4x10 face mounted joist hangers (HGUS410)

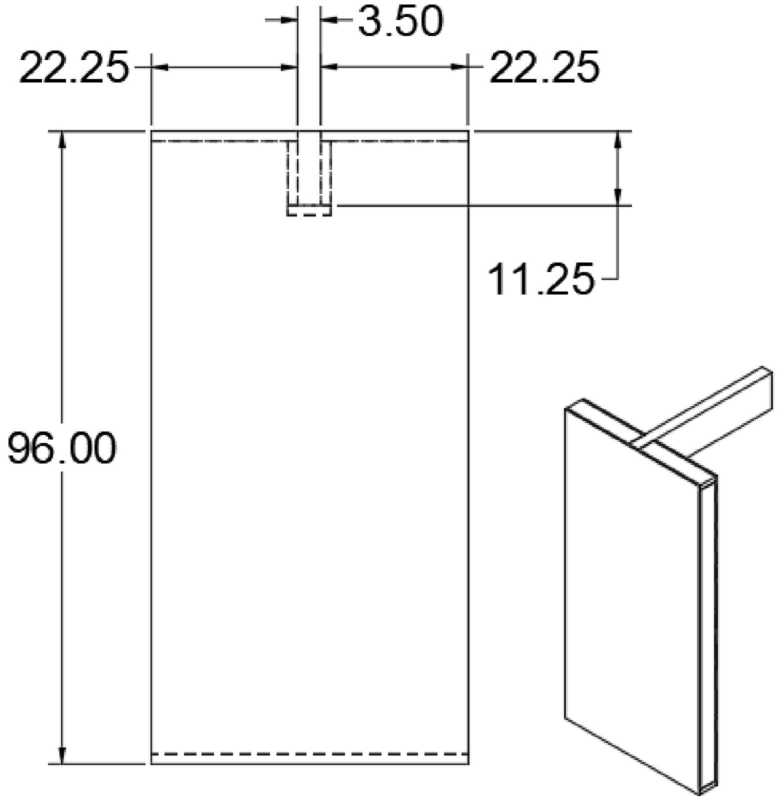
Phase 2 Specimens (2021)

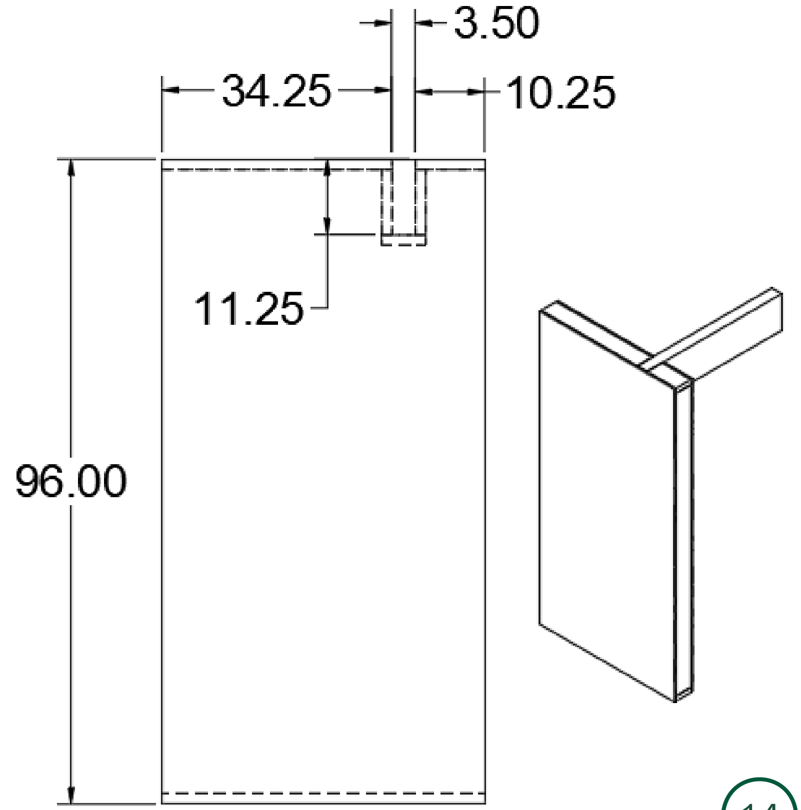
- 3.5"x12" Beam pocket
- One face of plywood cut
- Beam wrapped with 2x6s and nailed
- Foam over-cut to allow 2x6 wrap
- Beam and wrap nailed and glued



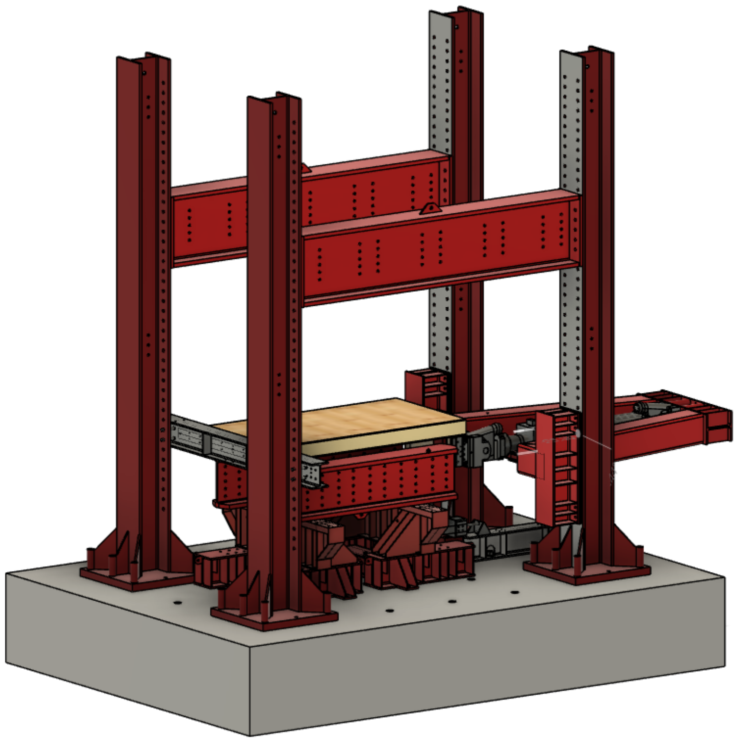
Phase 2 Specimens (2021)

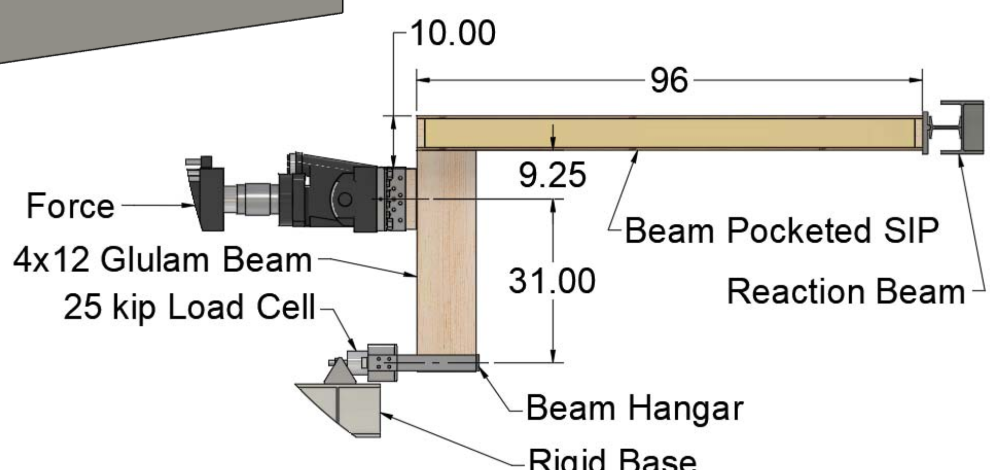
(4) Pockets tests at Center and (4) at Offset (near edge)



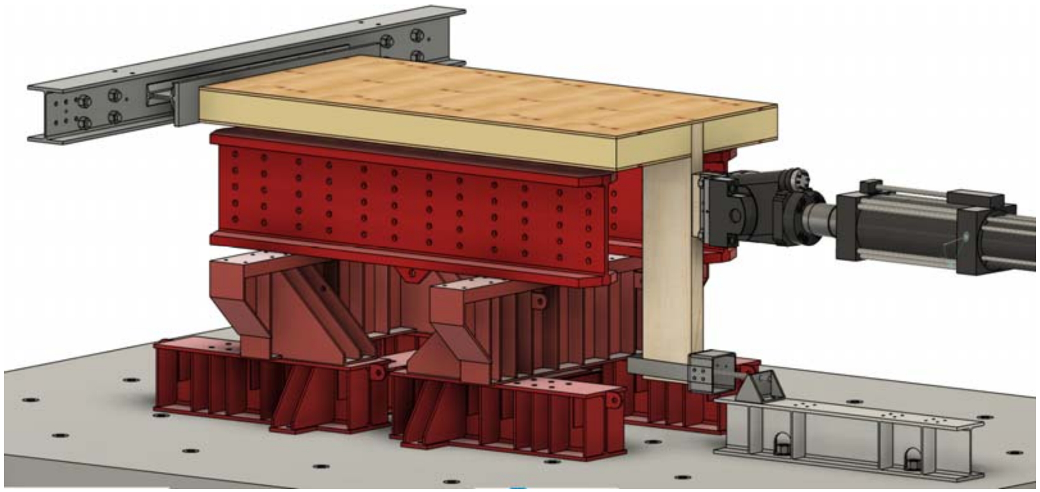


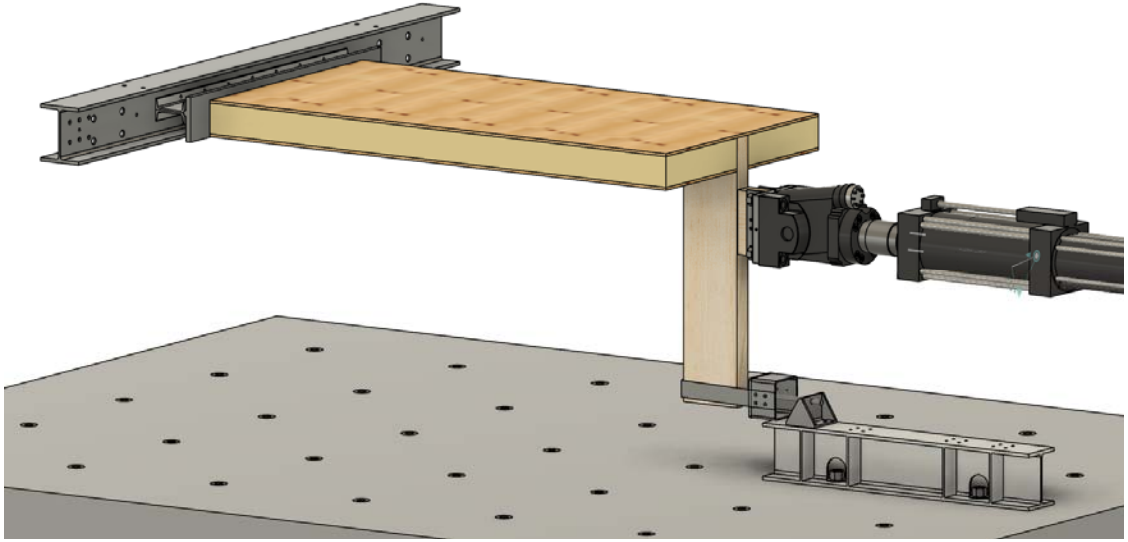
Phase 2 Setup





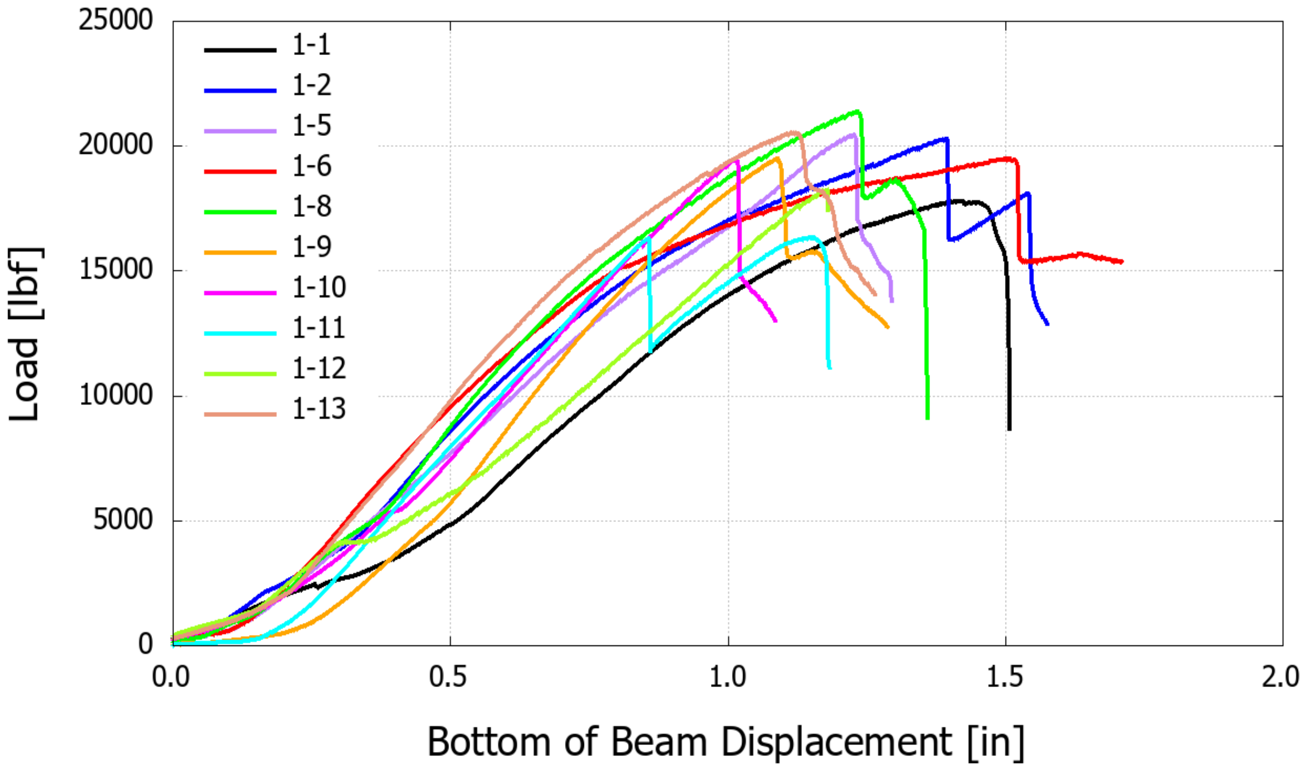
Phase 2 Setup





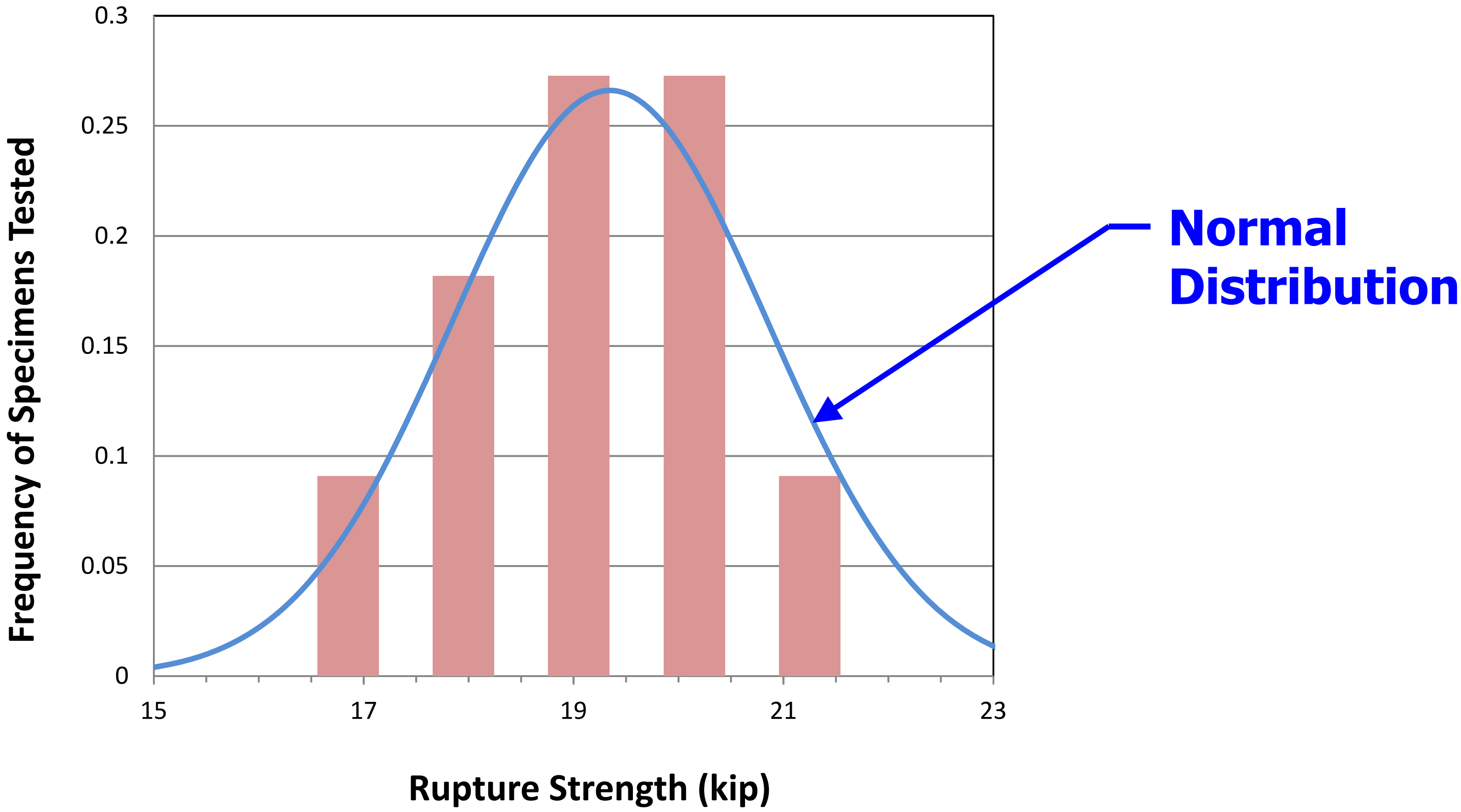
Beam-Pocket Test Results

Phase 1 Results



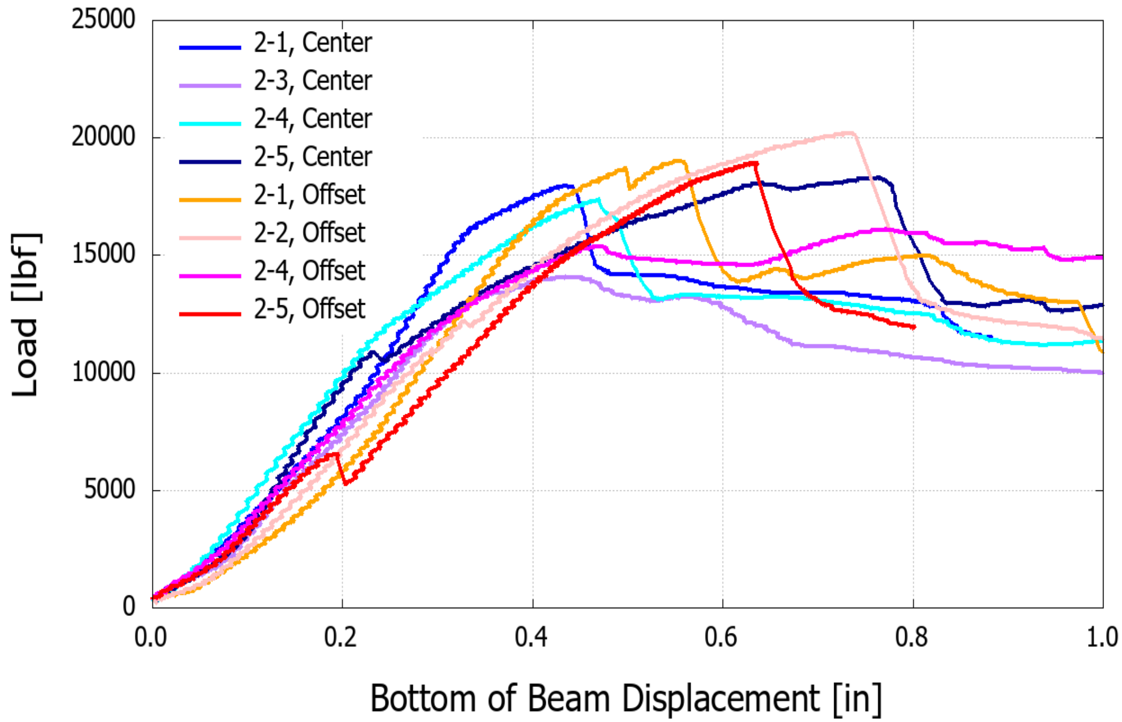
Specimen	Max. Force (lbf)
1-1	17,795
1-2	20,260
1-5	20,441
1-6	19,491
1-8	21,378
1-9	19,501
1-10	19,453
1-11	16,351
1-12	18,248
1-13	20,540
Mean	19,346
St. Dev.	1,499
COV	0.077

Phase I Distribution



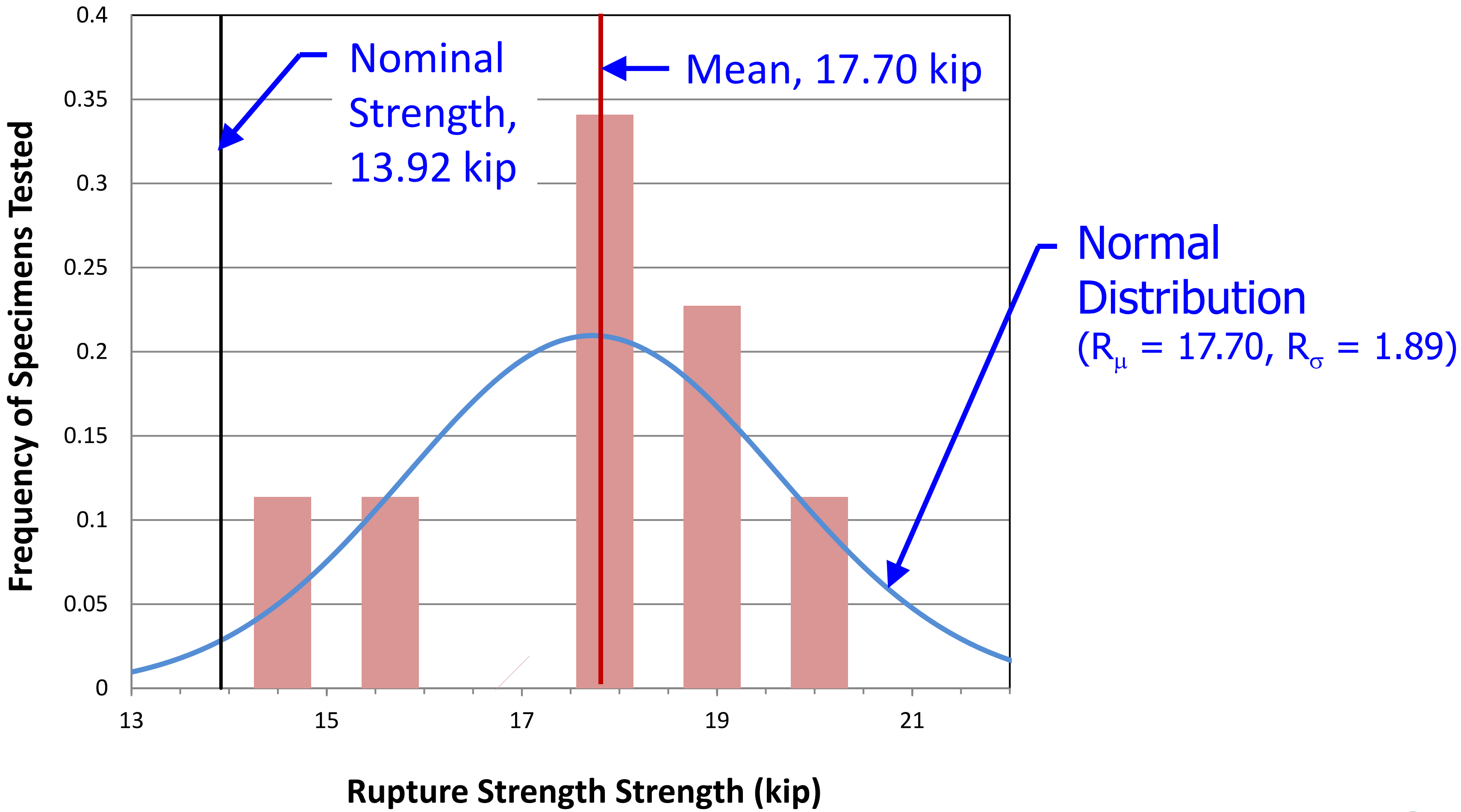
Phase 2 Results

- Audio Indications of Failure
- Non-Sudden Failure
- Center Pockets ~20% Stiffer than offset



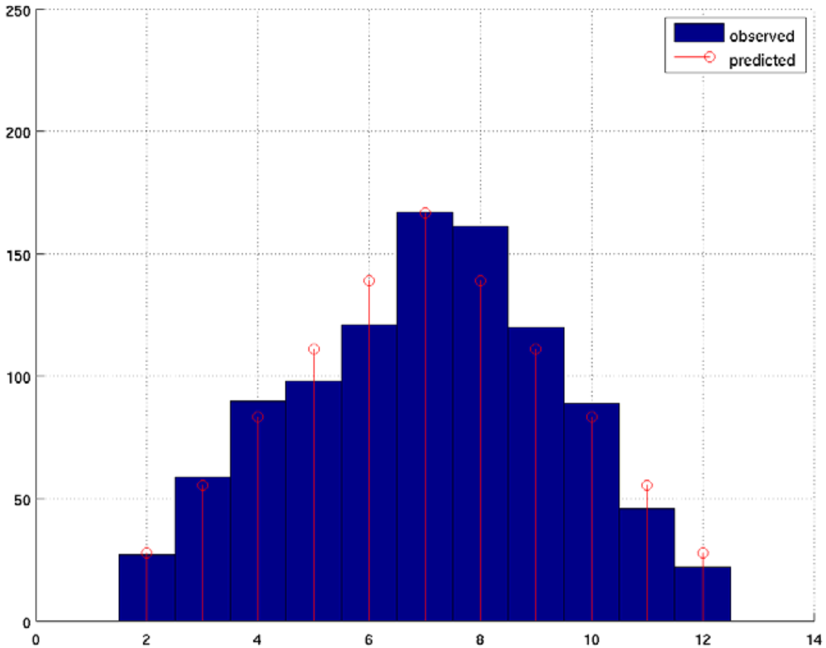
Speci-men	Beam Location	Max Force (lbf.)	Stiffness (lbf/in)
2-1	Center	17,941	46,506
2-3	Center	14,080	42,286
2-4	Center	17,364	52,178
2-5	Center	18,314	59,945
2-1	Offset	18,900	39,665
2-2	Offset	20,200	44,594
2-4	Offset	16,092	42,389
2-5	Offset	18,900	38,144
Mean		17,724	45,713
St Dev		1,904	7,200
COV		0.107	0.158

Phase 2 Distribution

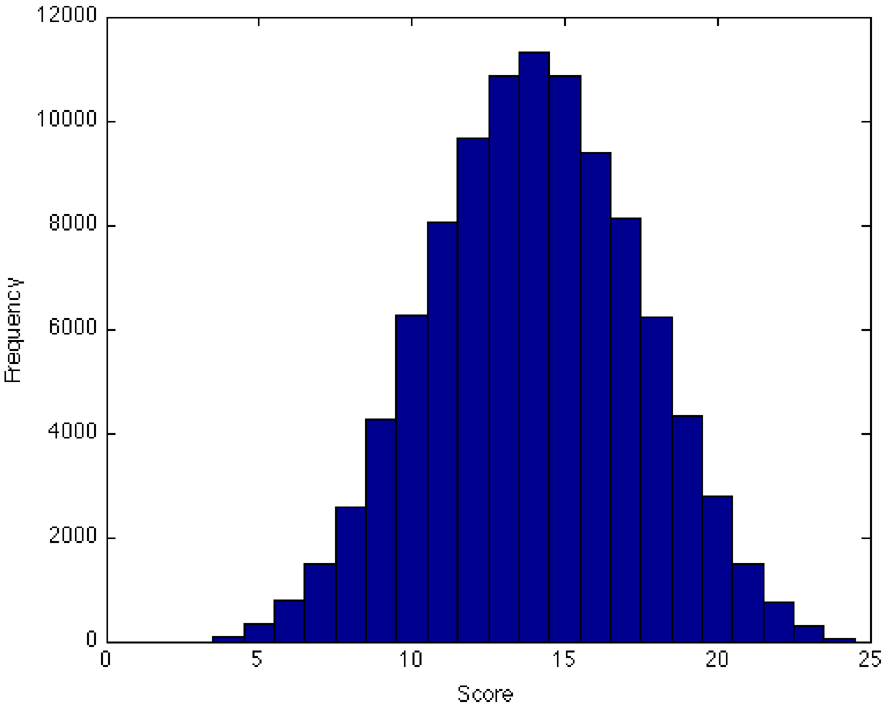


Review of Probability and Reliability

A Review of Probability

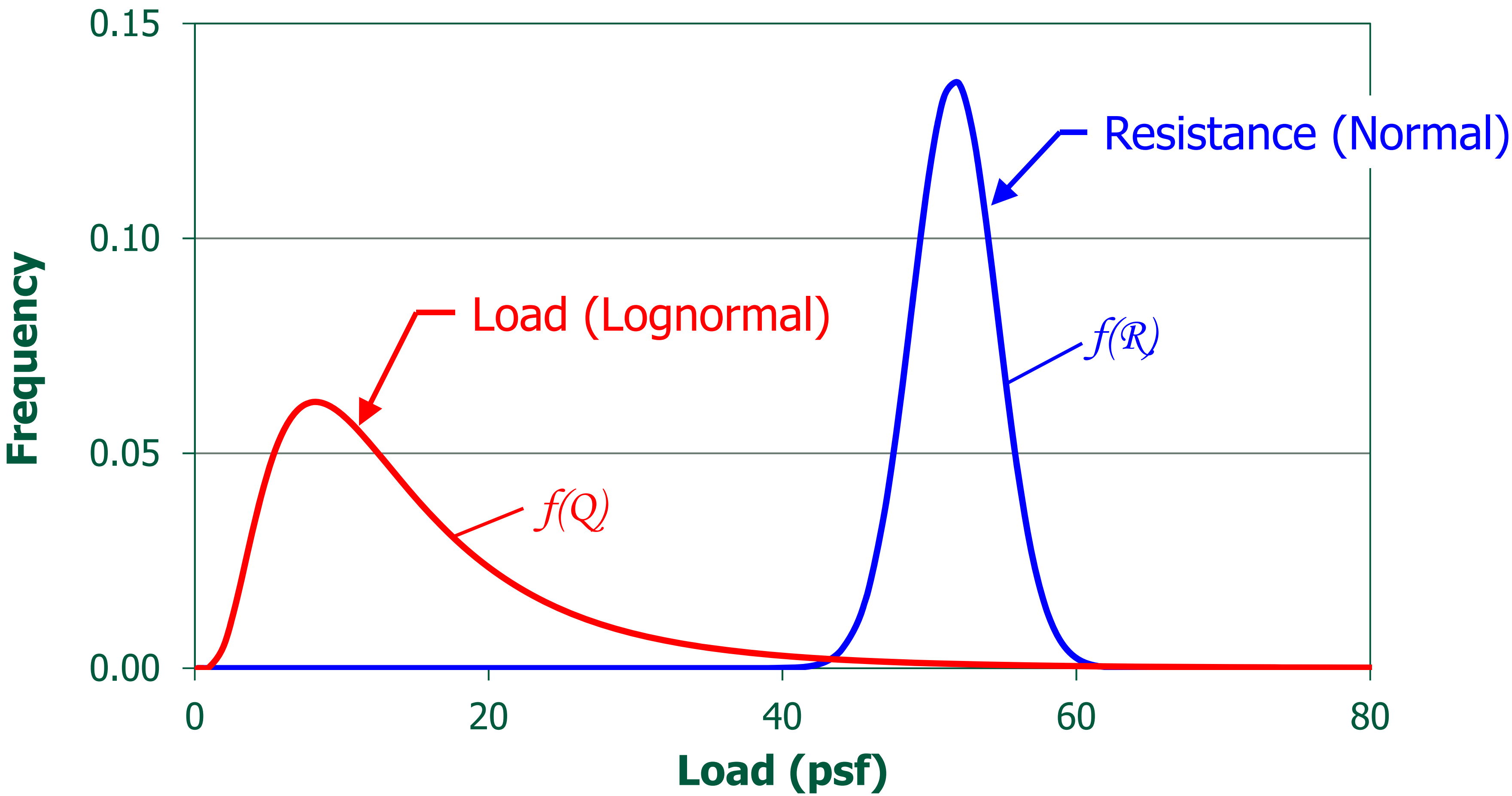


2 Dice Histogram (1000 rolls)



4 Dice Histogram (100,000 rolls)

Probabilistic Design



Reliability Analysis

$$P_f = \Phi\left[-\frac{R_m - Q_m}{\sqrt{\sigma_R^{\ 2} + \sigma_Q^{\ 2}}}\right] = \Phi[-\beta] \longrightarrow \beta = \frac{R_m - Q_m}{\sqrt{\sigma_R^{\ 2} + \sigma_Q^{\ 2}}}$$

β = Reliability Index

P_f = Probability of Failure

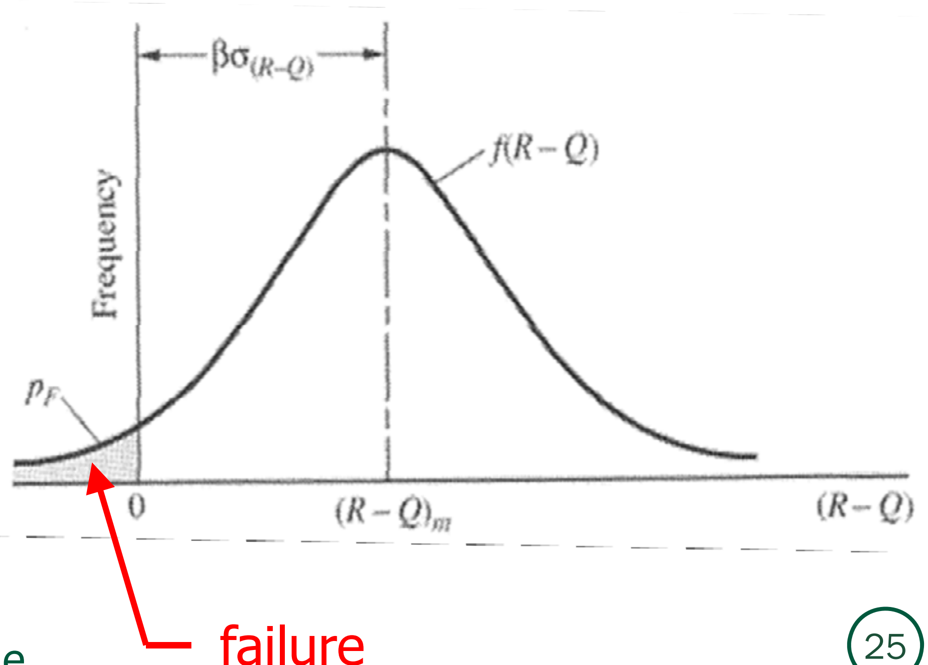
R_m = Mean of Resistance

Q_m = Mean of Load

σ_R = Standard deviation of Resistance

σ_Q = Standard deviation of Load

R and Q are normally distributed



$\Phi()$ is the CDF of the standard normal variable

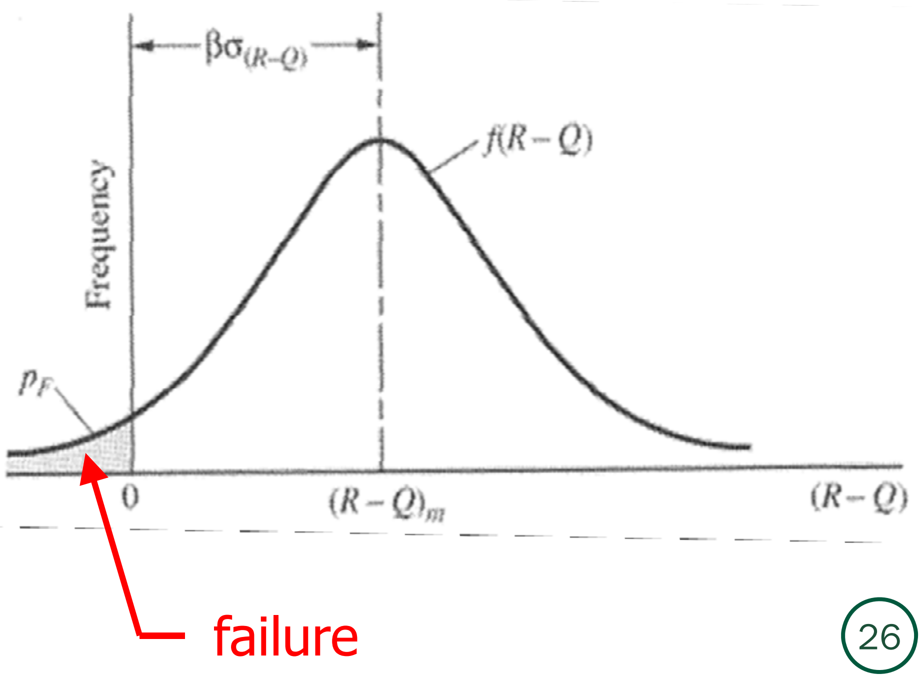
Reliability Analysis

$$P(f) = \int_0^{\infty} F_R(x) \cdot f_Q(x)\, dx$$

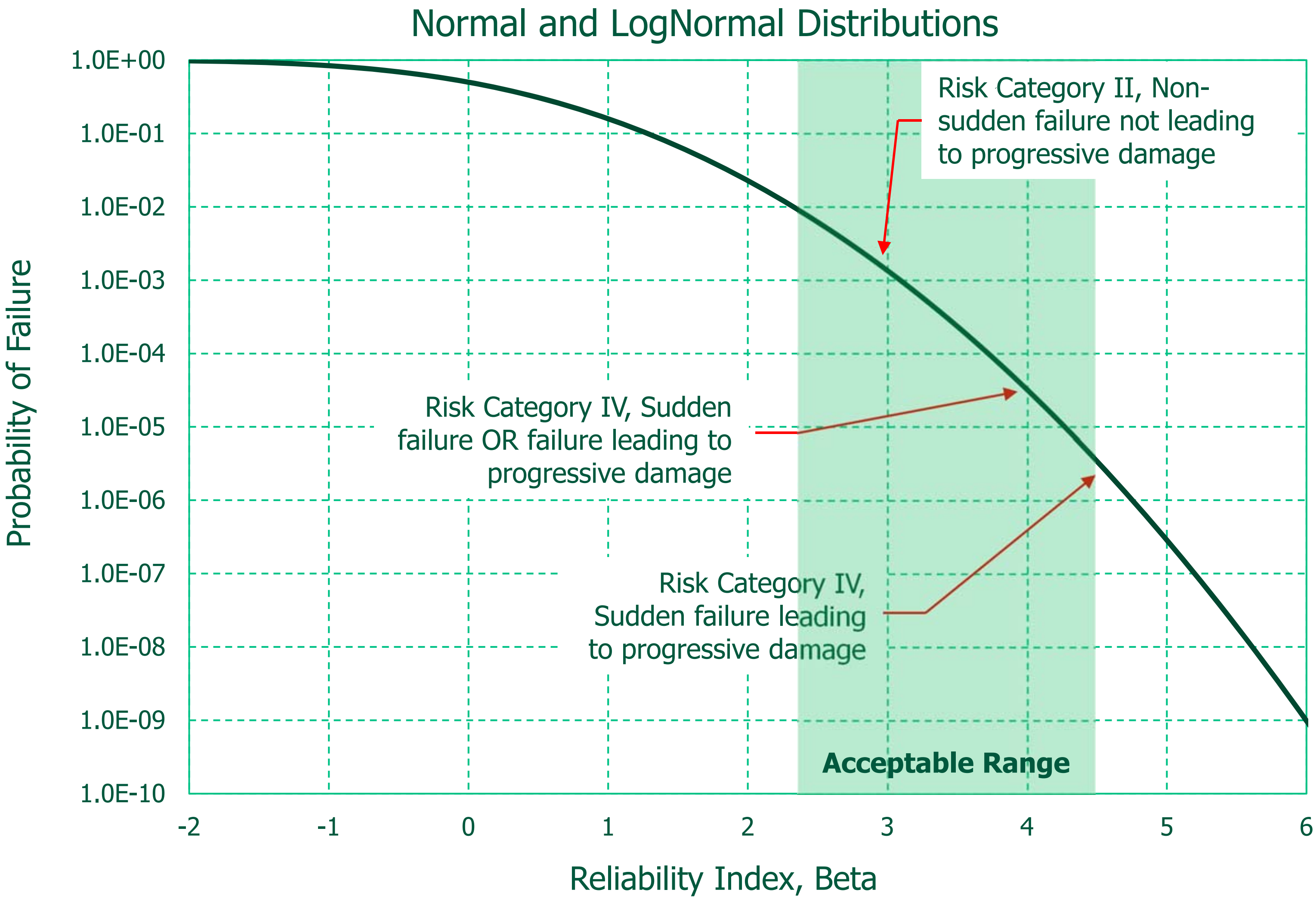
P(f) = Probability of Failure

F_R = Cumulative distribution (CDF) of Resistance

f_Q = Probability density (PDF) of Load



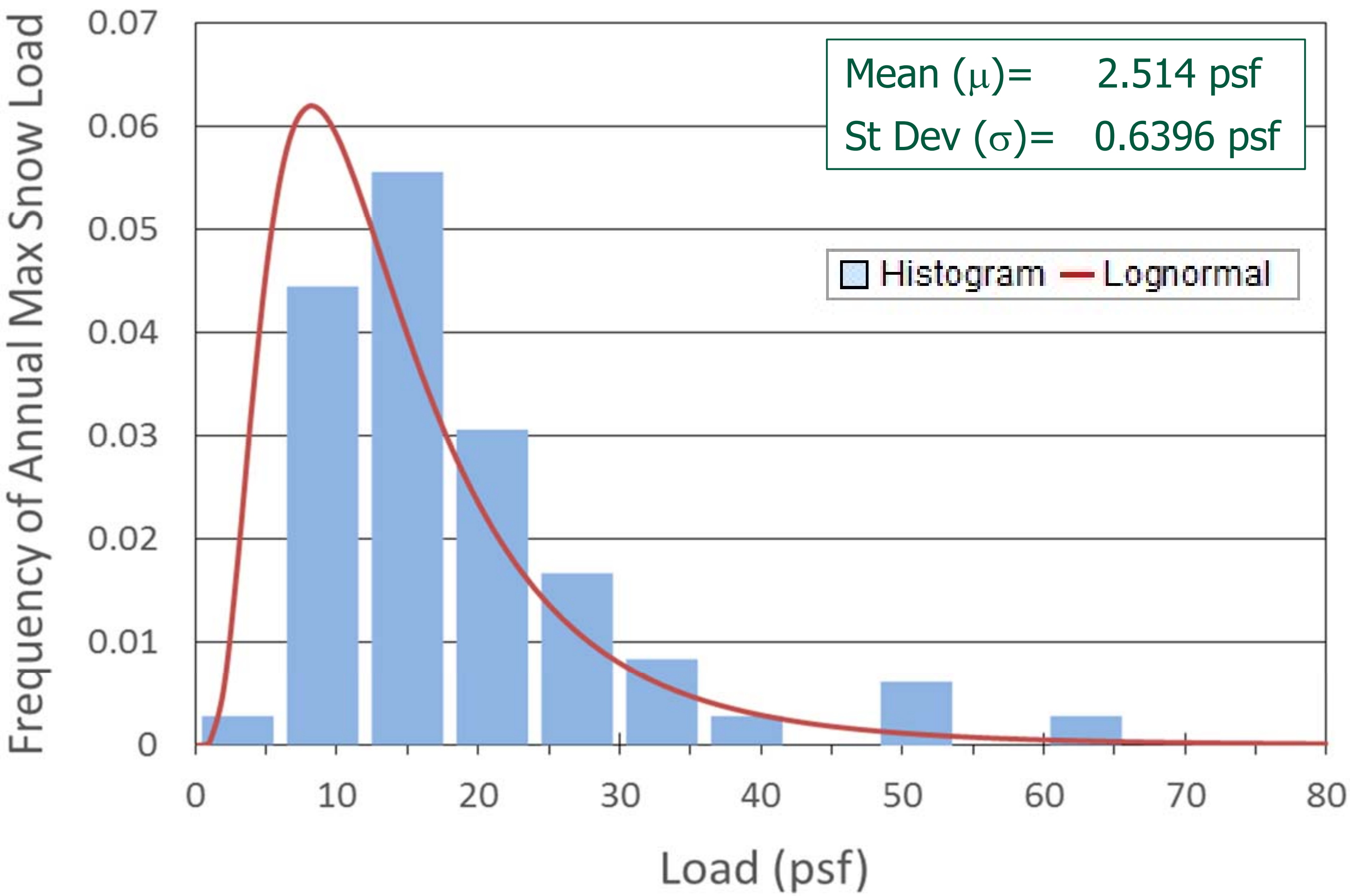
Probability of Failure vs. Beta Curve



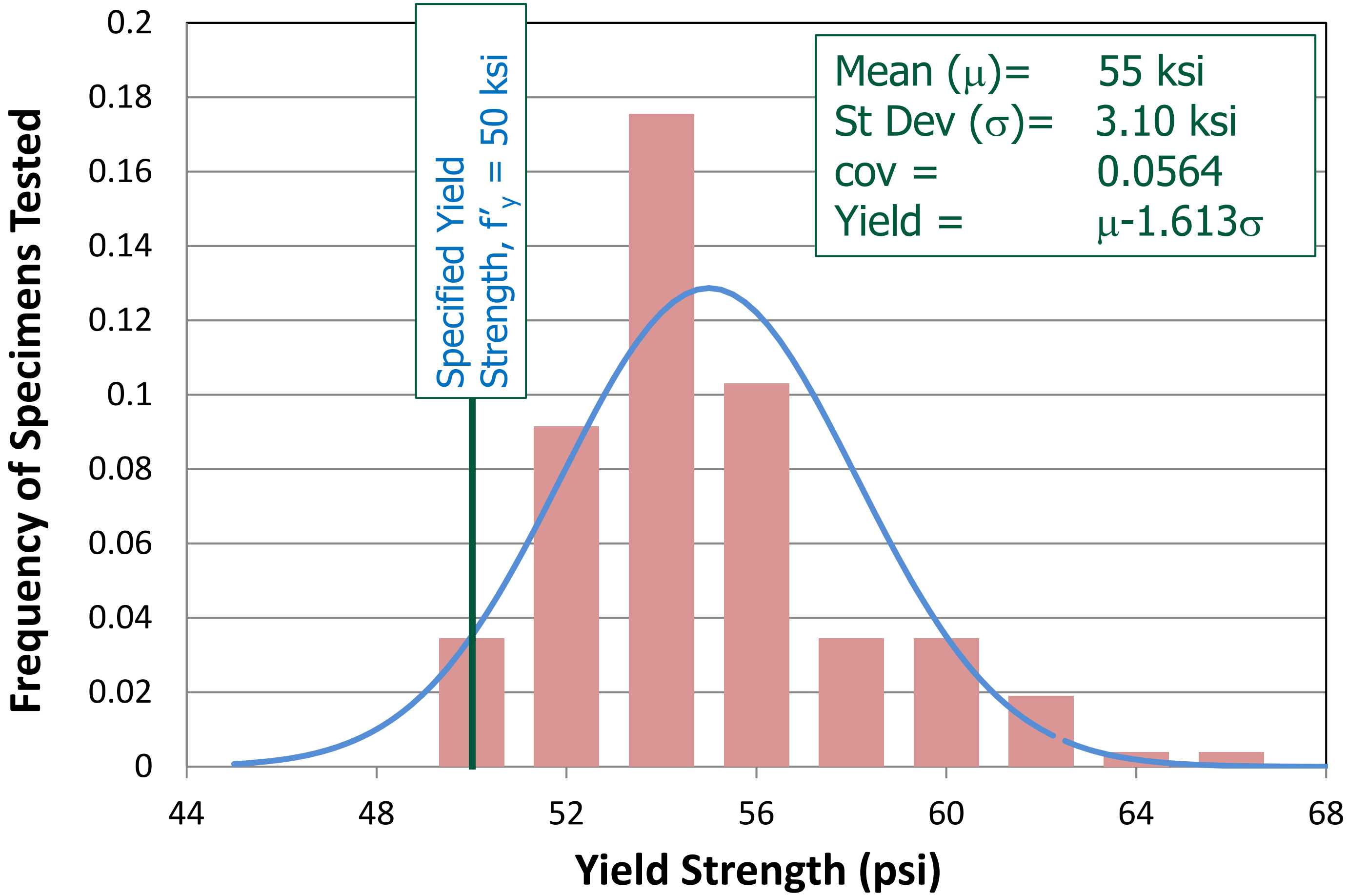
Quick Example Problem

Snow Load Frequency

Anchorage Airport 1959-2016

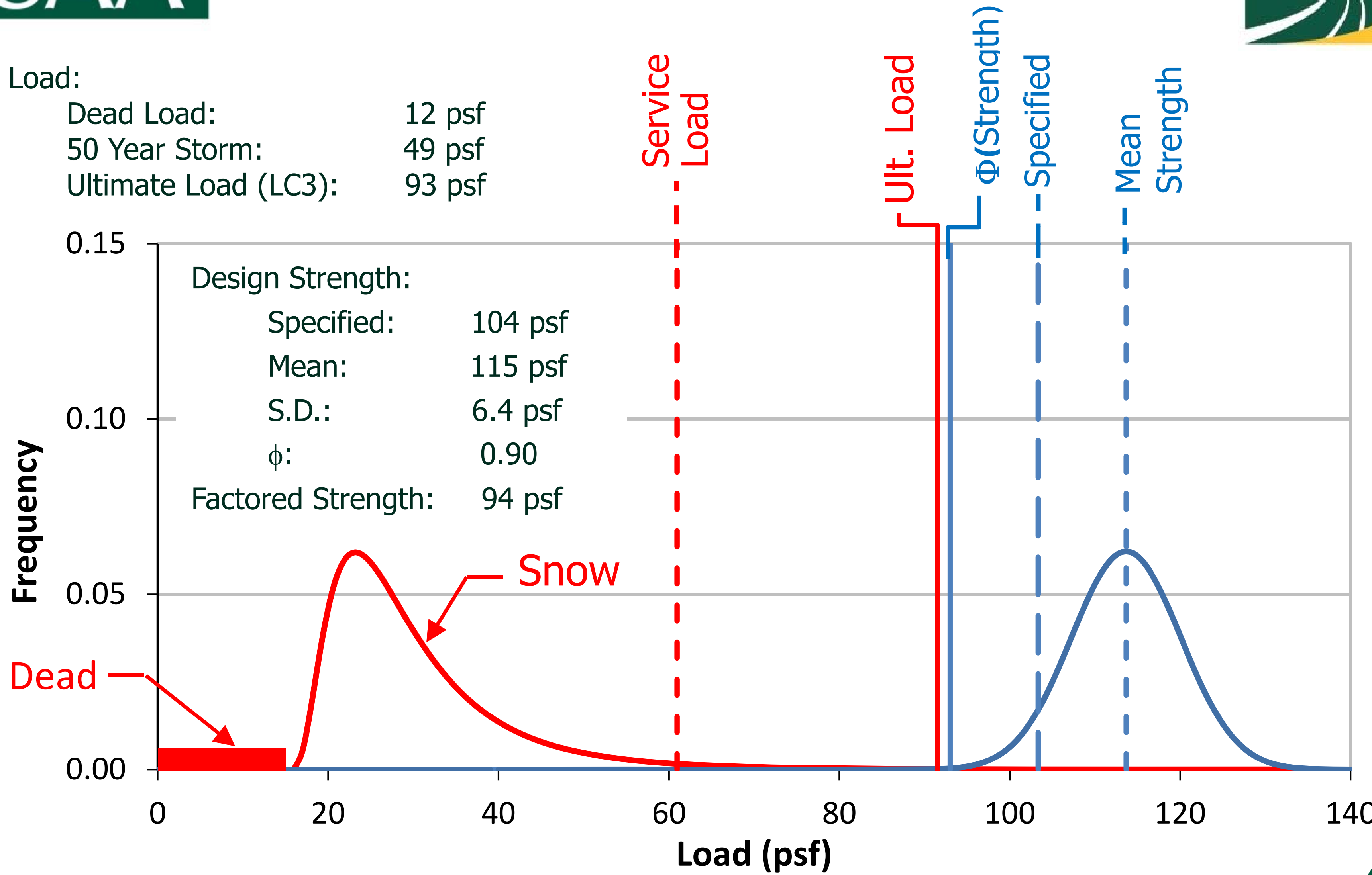


Strength Variation



Bartlett, F. M., Dexter, R. J., Graeser, M. D., Jelinek, J. J., Schmidt, B. J., and Galambos, T. V. (2003). "Updating Standard Shape Material Properties Database for Design and Reliability." *AISC Engineering Journal*, 40(1), 2–14.

LRFD Example



Probability of Failure: 2.7×10^{-4}

$\beta = 3.46$

Reliability Targeted Analysis

Reliability Targeted Analysis

- Section 1.3.1.3 of ASCE 7-16 allows structural components to be designed with performance-based procedures
- Must be demonstrated through analysis and testing that the design provides a reliability that is consistent with given target reliabilities

An overview of reliability analysis can be found in Nowak and Collins, *Reliability of structures*, 2nd ed. Boca Raton, FL: CRC Press, 2012.

Target Reliabilities

Table 1.3-1 Target Reliability (Annual Probability of Failure, P_F) and Associated Reliability Indices (β)[1] for Load Conditions That Do Not Include Earthquake, Tsunami, or Extraordinary Events[2]

	Risk Category			
Basis	**I**	**II**	**III**	**IV**
Failure that is not sudden and does not lead to widespread progression of damage	$P_F = 1.25 \times 10^{-4}/\text{yr}$ $\beta = 2.5$	$P_F = 3.0 \times 10^{-5}/\text{yr}$ $\beta = 3.0$	$P_F = 1.25 \times 10^{-5}/\text{yr}$ $\beta = 3.25$	$P_F = 5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$
Failure that is either sudden or leads to widespread progression of damage	$P_F = 3.0 \times 10^{-5}/\text{yr}$ $\beta = 3.0$	$P_F = 5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$	$P_F = 2.0 \times 10^{-6}/\text{yr}$ $\beta = 3.75$	$P_F = 7.0 \times 10^{-7}/\text{yr}$ $\beta = 4.0$
Failure that is sudden and results in widespread progression of damage	$P_F = 5.0 \times 10^{-6}/\text{yr}$ $\beta = 3.5$	$P_F = 7.0 \times 10^{-7}/\text{yr}$ $\beta = 4.0$	$P_F = 2.5 \times 10^{-7}/\text{yr}$ $\beta = 4.25$	$P_F = 1.0 \times 10^{-7}/\text{yr}$ $\beta = 4.5$

[1]The target reliability indices are provided for a 50-year reference period, and the probabilities of failure have been annualized. The equations presented in Section 2.3.6 are based on reliability indices for 50 years because the load combination requirements in Section 2.3.2 are based on the maximum loads for the 50-year reference period.
[2]Commentary to Section 2.5 includes references to publications that describe the historic development of these target reliabilities.

Design Parameters

- Two design parameters must be chosen to determine β with the established resistance distribution
- For this analysis, these were chosen as:

1) Nominal Resistance Ratio: $\frac{Mean\ Resistance}{Nominal\ Resistance}$

   Nominal Resistance was chosen as two standard deviations below mean strength: $R_n = R_\mu - 2 \cdot R_\sigma$

2) LRFD Resistance Factor: ϕ such that $\phi R_n \geq R_u$

   ϕ was varied until β > 3.0

Load Distributions

- Two Load combinations were investigated:
    1) Dead + Live
    2) Dead + Snow
- Other Parameters were used from ASCE 7

Load	X_μ/X_n	COV	Distribution
Dead	1.05	0.10	Normal
Live	1.00	0.25	GEV Type I
Snow[1]	1.00	-	Lognormal

[1] Site specific 50-year return period (annual probability of occurrence = 0.02)

Combining Loads

- Concurrent loads, each with a different distribution, must be combined into load combinations (summing random variables).
- Method to do this is called "convolution":

$$f_Z(x) = \int_{-\infty}^{\infty} f_X(t) \cdot f_Y(x - t)\, dt$$

where:

X and Y are random variables and Z is joint variable

Combining Loads

Resulting (D+L) and (D+S) equations

$$f_{D+L}(x) = \int_0^{\infty} \frac{exp\left[\left(\frac{-(x-t-\mu_D)^2}{2\cdot{\sigma_D}^2}\right) - \left(\frac{t-\mu_L}{\sigma_L}\right) - \exp\left(-\left(\frac{t-\mu_L}{\sigma_L}\right)\right)\right]}{\sigma_D \cdot \sqrt{2\pi}}\, dt$$

$$f_{D+S}(x) = \int_0^{\infty} \frac{exp\left[\left(\frac{-(x-t-\mu_D)^2}{2\cdot{\sigma_D}^2}\right) - \frac{(\ln(t)-\mu_S)^2}{2\cdot{\sigma_S}^2}\right]}{2\pi\cdot\sigma_D\cdot\sigma_S\cdot t}\, dt$$

Evaluated in Mathcad:

$DeadSnow :=$ for $z \in 0..219$

$x \leftarrow 0.1 + 0.1\,z$

$C_{z,0} \leftarrow x$

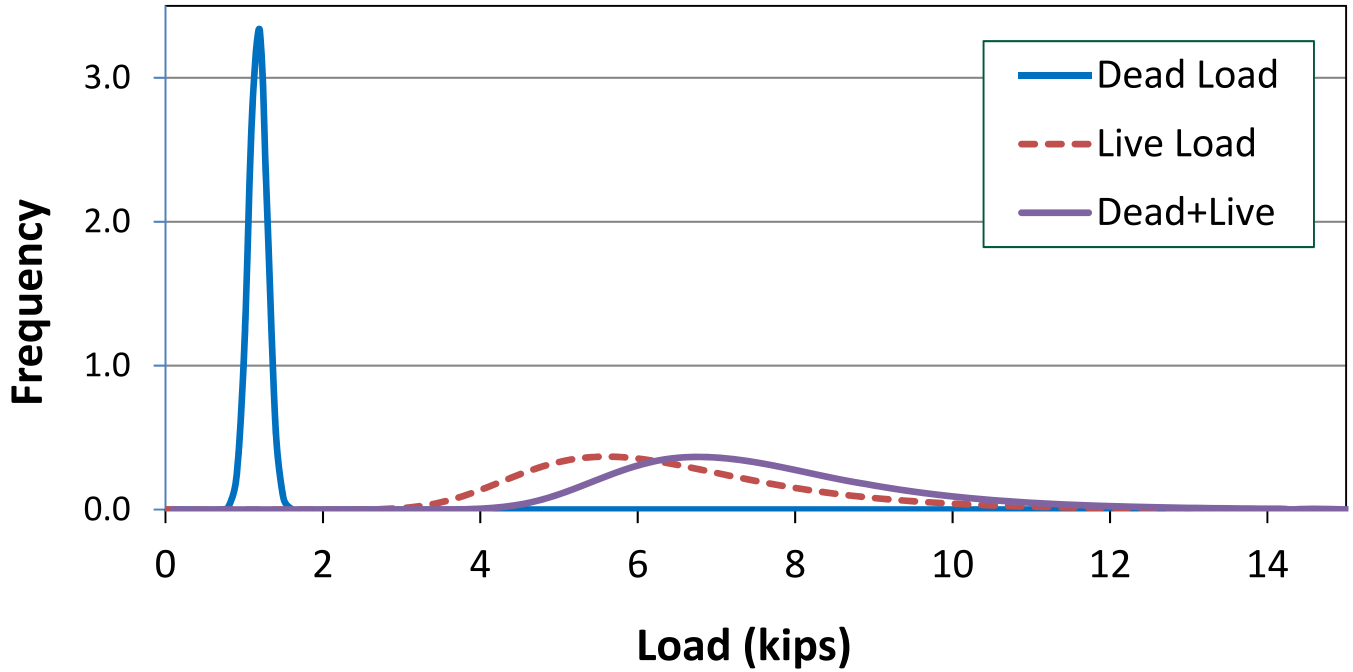
$$C_{z,1} \leftarrow \int_0^{20} \frac{\exp\left(\frac{-(x-t-\mu_1)^2}{2\,{\sigma_1}^2} + -\left(\frac{t-\mu_2}{\sigma_2}\right) + -\exp\left(-\left(\frac{t-\mu_2}{\sigma_2}\right)\right)\right)}{\sqrt{2\cdot\pi\cdot{\sigma_1}^2}}\, dt$$

C

Combining Loads (D+L)

To align units, a floor area of 140 ft^2 was chosen:

	Basis	Nominal (kips)	Mean (kips)	St. Dev. (kips)
Dead	8 psf	1.12	1.18	0.118
Live	40 psf	5.60	5.60	1.40



Analytical Evaluation of Live Load Reliability

- Load distribution shape established (convolution)
- Resistance distribution shape and magnitude established
- Choose ϕ to locate magnitude of load curve
- β can be evaluated (numerically):

$$\beta = -\Phi\left(\int_0^{\infty} F_R(x) \cdot f_Q(x)\, dx\right)$$

Using excel:

	A	B	C	D	E	F	G	H
1–2	Load (kips)	$f_D(x)$	$f_L(x)$	$f_{D+L}(x)$	$f_R(x)$	$F_R(x)$	$F_R(x) \cdot f_Q(x)$	$\sum\left(F_R(x) \cdot f_Q(x)\right)$
3	0.01	1.52583E-21	1.55298E-22		2.38986E-20	4.7933E-21	0	
4	0.1	2.24773E-18	4.25695E-21	7.87638E-42	3.72049E-20	7.49944E-21	5.90685E-62	5.90685E-62
5	0.2	3.74698E-15	1.31828E-19	2.06533E-38	6.06788E-20	1.22994E-20	2.54023E-58	1.27632E-59
6	0.3	3.03102E-12	3.20628E-18	2.51544E-35	9.86879E-20	2.01161E-20	5.06008E-55	2.53259E-56
7	0.4	1.18978E-09	6.22742E-17	1.4552E-32	1.60059E-19	3.281E-20	4.77451E-52	2.39232E-53
8	0.5	2.2663E-07	9.8099E-16	4.16509E-30	2.58873E-19	5.3367E-20	2.22278E-49	1.11617E-50
9	0.6	2.09478E-05	1.27157E-14	6.23789E-28	4.17526E-19	8.6565E-20	5.39983E-47	2.72219E-48
10	0.7	0.000939575	1.37459E-13	5.12097E-26	6.71536E-19	1.40028E-19	7.17081E-45	3.63962E-46
11	0.8	0.020450056	1.25486E-12	2.39165E-24	1.07707E-18	2.25888E-19	5.40245E-43	2.77348E-44
12	0.9	0.215987603	9.78754E-12	7.50639E-23	1.72271E-18	3.63391E-19	2.72775E-41	1.41862E-42
13	1.0	1.106965842	6.59348E-11	2.18094E-21	2.74768E-18	5.82988E-19	1.27146E-39	6.63557E-41
14	1.1	2.753028324	3.87531E-10	5.05597E-20	4.37031E-18	9.32716E-19	4.71579E-38	2.48782E-39
15	1.2	3.32244808	2.00602E-09	6.86326E-19	6.93183E-18	1.48814E-18	1.02135E-36	5.59132E-38
16	1.3	1.945704083	9.22572E-09	8.14007E-18	1.09641E-17	2.36779E-18	1.92739E-35	1.07068E-36
17	1.4	0.552925274	3.80054E-08	1.65142E-16	1.72937E-17	3.75704E-18	6.20447E-34	3.30567E-35
18	1.5	0.076247772	1.41308E-07	2.4919E-15	2.72015E-17	5.94504E-18	1.48145E-32	8.04802E-34

D+L Reliability Relations

Load:

Dead Load: R_D = 1.36 kips

Live Load: R_L = 6.80 kips

Ult. Load (1.2D+1.6L): R_u = 12.50 kips

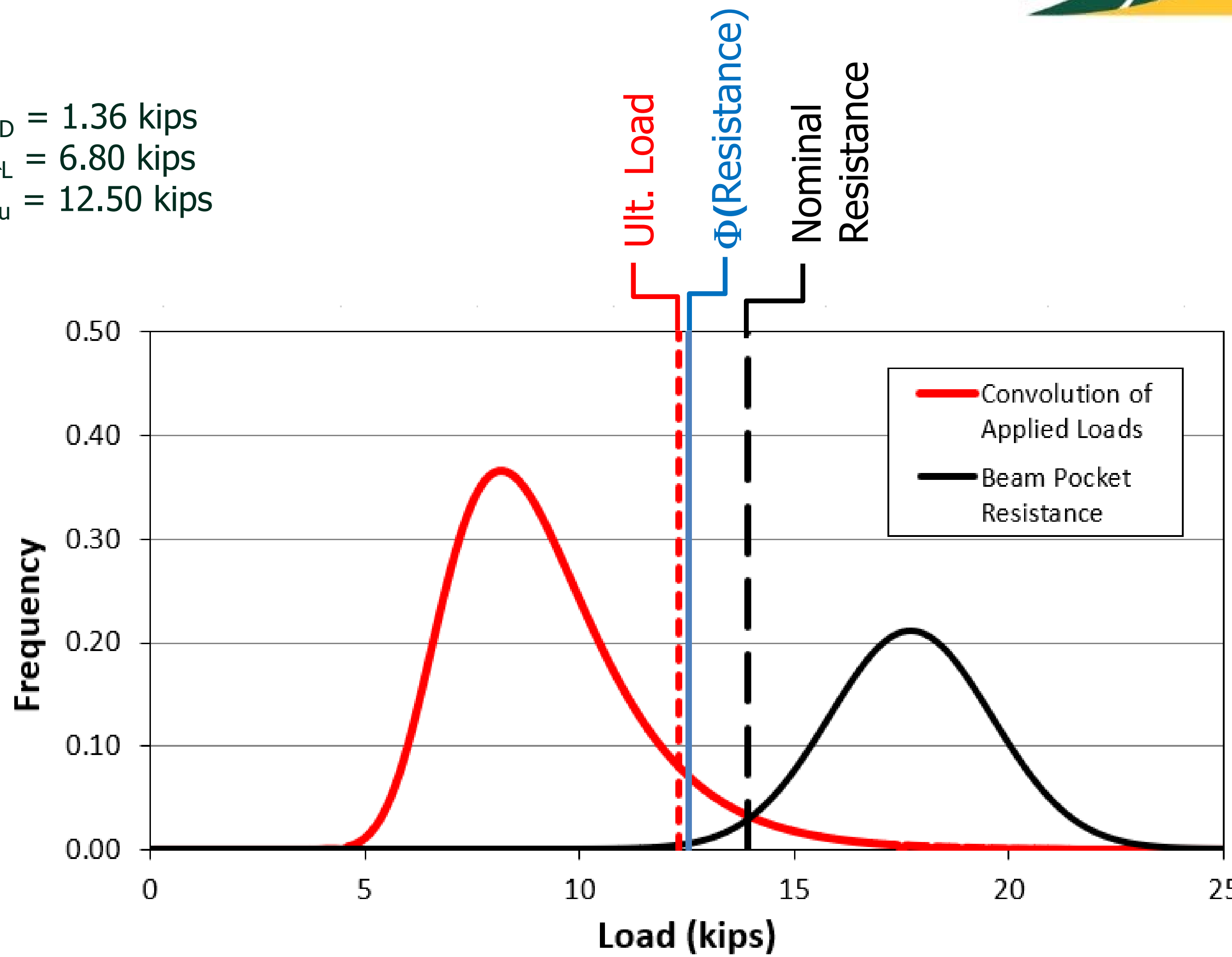
Resistance:

Mean: R_μ = 17.70 kips

Nominal: R_n = 13.92 kips

Factor: ϕ= 0.90

Design: ϕR_n= 12.52 kip



β=2.32

ϕR_n = 12.52 kip > R_u = 12.50 kips

Increase ϕ to improve β

<u>Load:</u>

Dead Load: R_D = 1.12 kips

Live Load: R_L = 5.6 kips

Ult. Load (1.2D+1.6L): R_u = 10.30 kips

<u>Resistance:</u>

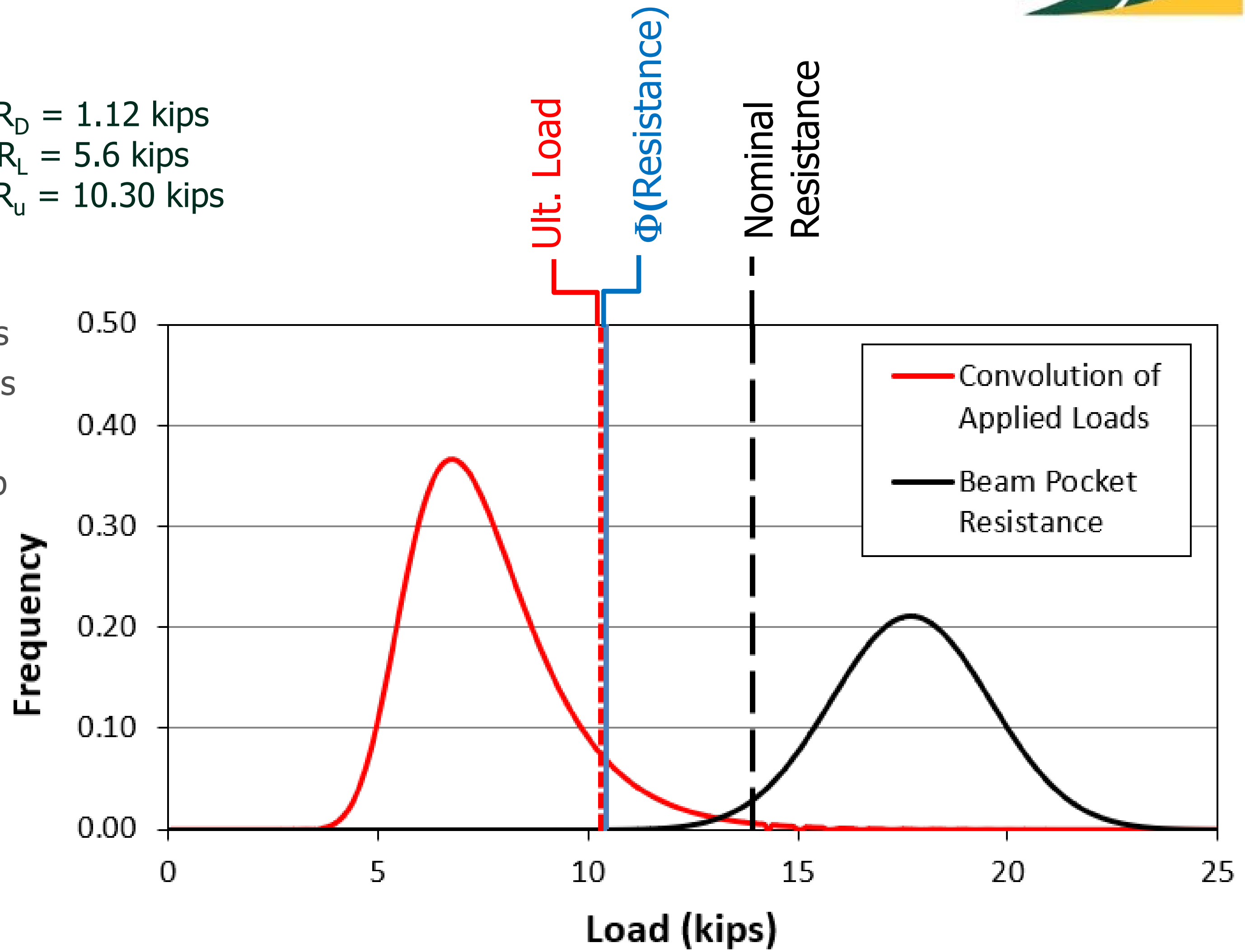
Mean: R_μ = 17.70 kips

Nominal: R_n = 13.92 kips

Factor: ϕ= 0.75

Design: ϕR_n= 10.44 kip

β=3.03

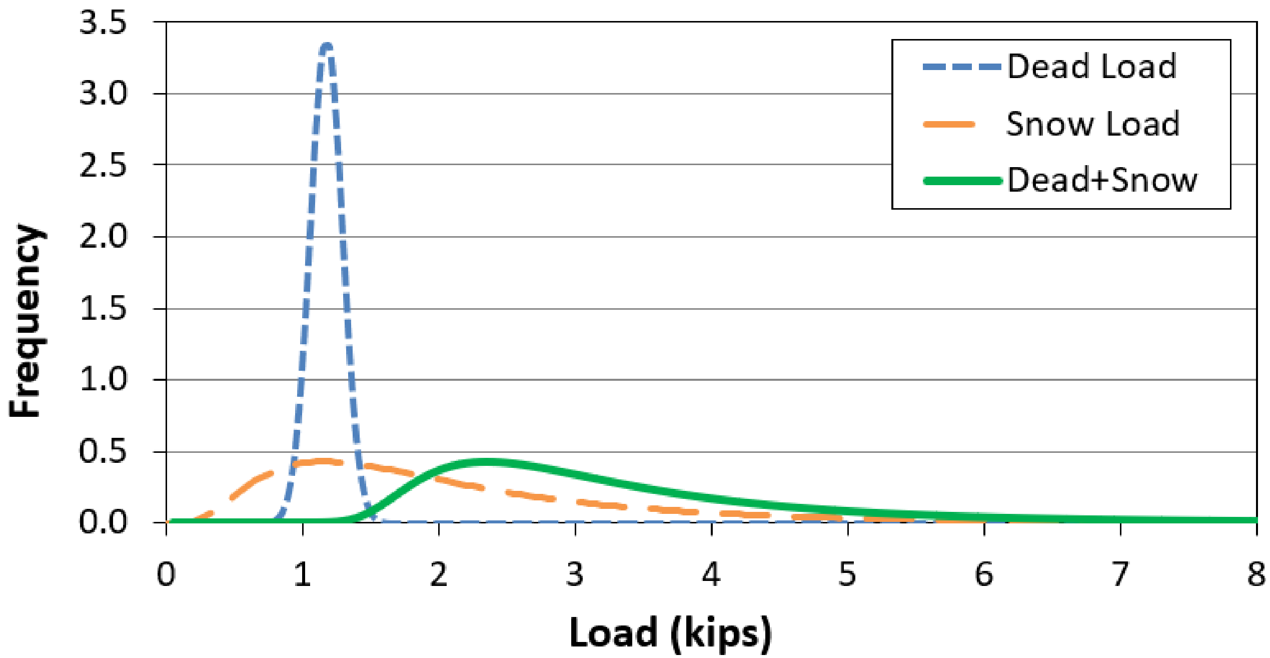


ϕR_n = 10.44 kip > R_u = 10.30 kips

Combining Loads (D+S)

Convolution of Dead and Snow:

	Basis	Nominal (kips)	Mean (kips)	St. Dev. (kips)
Dead	8 psf	1.12	1.18	0.118
Snow (Anchorage)	50 psf	0.570	0.570	0.651



Statistical Evaluation of Snow Load Reliability

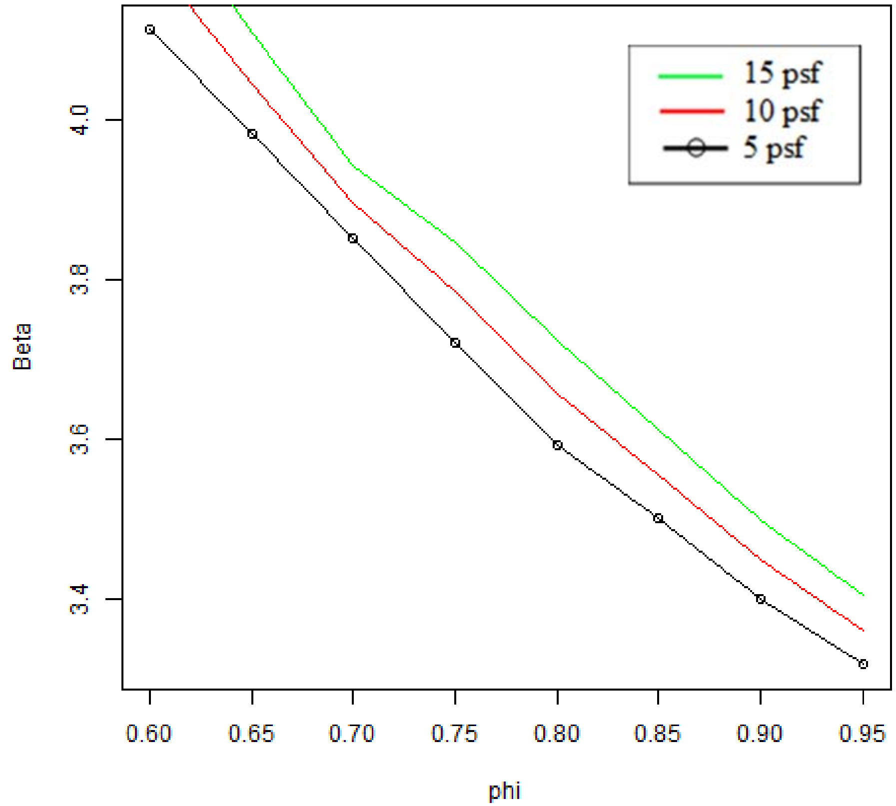
- Different method necessary to evaluate 48 stations economically
- Monte-Carlo Simulation
  - Snow load, Dead Load, and Resistance each sampled from distributions
  - For each set of values, limit state equation (LS = R – D – S) was evaluated
  - Number of limit states values less than zero (failure) were counted
  - Repeated 1 million times, percentage of failures assessed
- Repeated for 12 different Dead-Snow Ratios
- Repeated for 8 different ϕ factors (0.60 to 0.95)
- Repeated for 48 Snow Load Stations

Statistical Evaluation of Snow Load Reliability

Executed using Statistics package R

```
runs <- 1000000                  #Number of Data Points to Sample
n_stations=48                    #Number of snow load stations

sipcov=0.107                     #Coefficient of variation of Resistance
DS.ratios <- c(0.025,0.05,0.075,0.10,0.125,0.15,0.175,0.20,0.225,0.25,0.275,0.30)   #Dead-snow ratios
phi.list <- c(0.60,0.65,0.70,0.75,0.80,0.85,0.90,0.95)

#Define lists and matrices to be filled
betalist <- c(1:12)
b.5.list <- c(1:8)
b.10.list <- c(1:8)
b.15.list <- c(1:8)
namelist <- c(1:n_stations+1)
beta.5.matrix <- matrix(0,nrow=8,ncol=n_stations+1)
beta.10.matrix <- matrix(0,nrow=8,ncol=n_stations+1)
beta.15.matrix <- matrix(0,nrow=8,ncol=n_stations+1)
result <- matrix(0,nrow=12,ncol=9)

#Read Data for snow load stations  (mu and sigma of lognormal distribution)
mysnow <- read.csv("MatlabSnowTables.csv", header=TRUE, sep=",",stringsAsFactors=FALSE)

#s.meanlist<- c(4.216,2.56,3.93,2.985)
#s.sdlist<-c(0.265,0.597,0.389,0.516)
s.meanlist<- mysnow[,2]    #get mean of lognormal distribution for each location
s.sdlist<- mysnow[,3]      #get sigma of lognormal distribution for each location

for (k in 1:n_stations){               #k is the station number
SNAME<-mysnow[k,1]                     #station name
s.meanlog=s.meanlist[k]                #station log mean
s.sd=s.sdlist[k]                       #station signma
s.mean=qlnorm(0.98,s.meanlog,s.sd)     #station normal mean
ratio.5 = 5/s.mean                     #Dead-snow ration for 5psf dead load
ratio.10 = 10/s.mean                   #Dead-snow ration for 10psf dead load
ratio.15 = 15/s.mean                   #Dead-snow ration for 15psf dead load

for (j in 1:8){                        #j is the number of phi factors
    for (i in 1:12) {                  #i is the number of Dead-Snow ratios
        DSratio=DS.ratios[i]           #Get Dead-Snow Ratio
        phi<-phi.list[j]               #Get phi factor

        d.nominal=s.mean*DSratio       #get nominal dead load for given dead-snow ratio
```

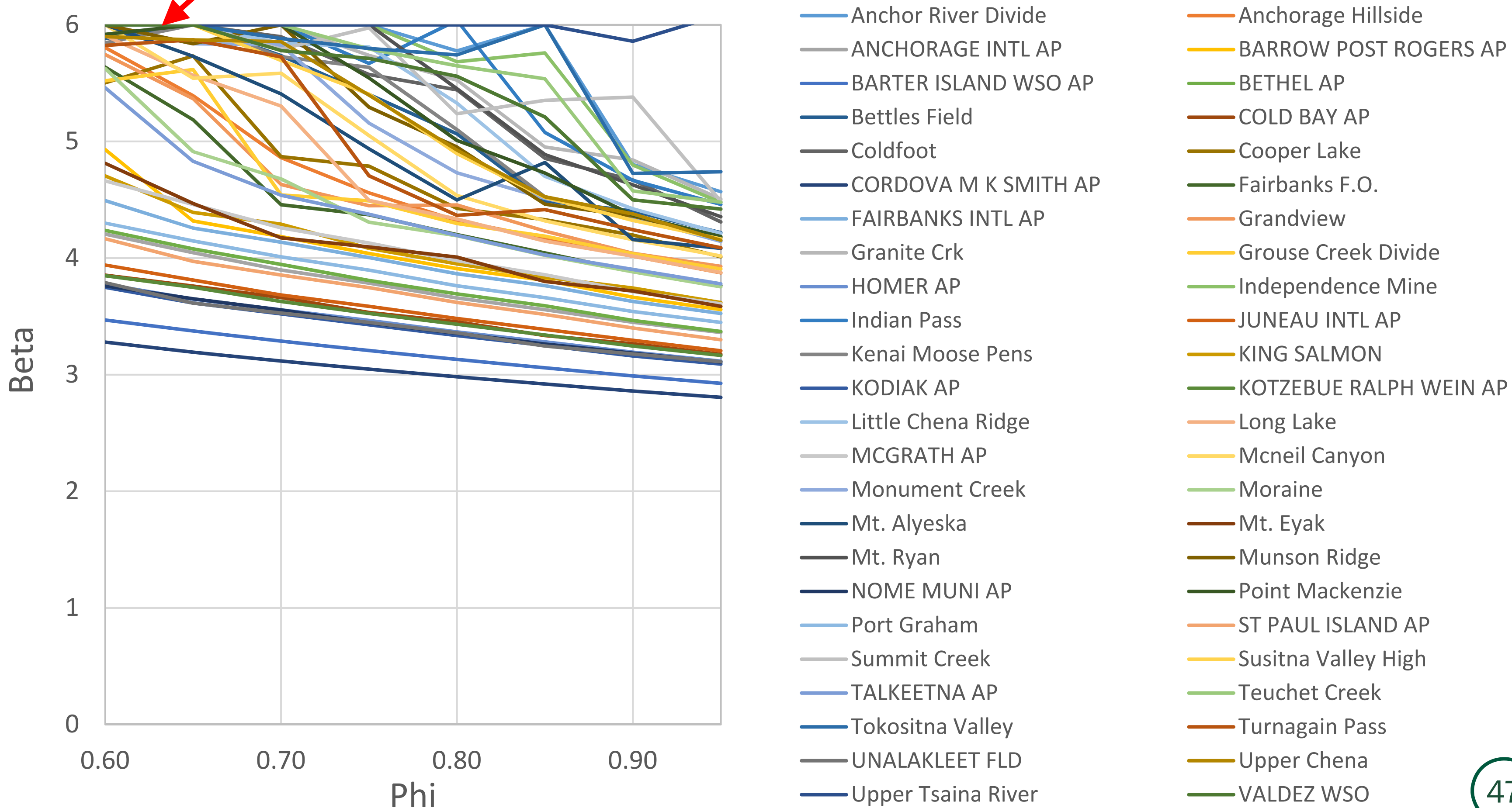
Monte-Carlo Results



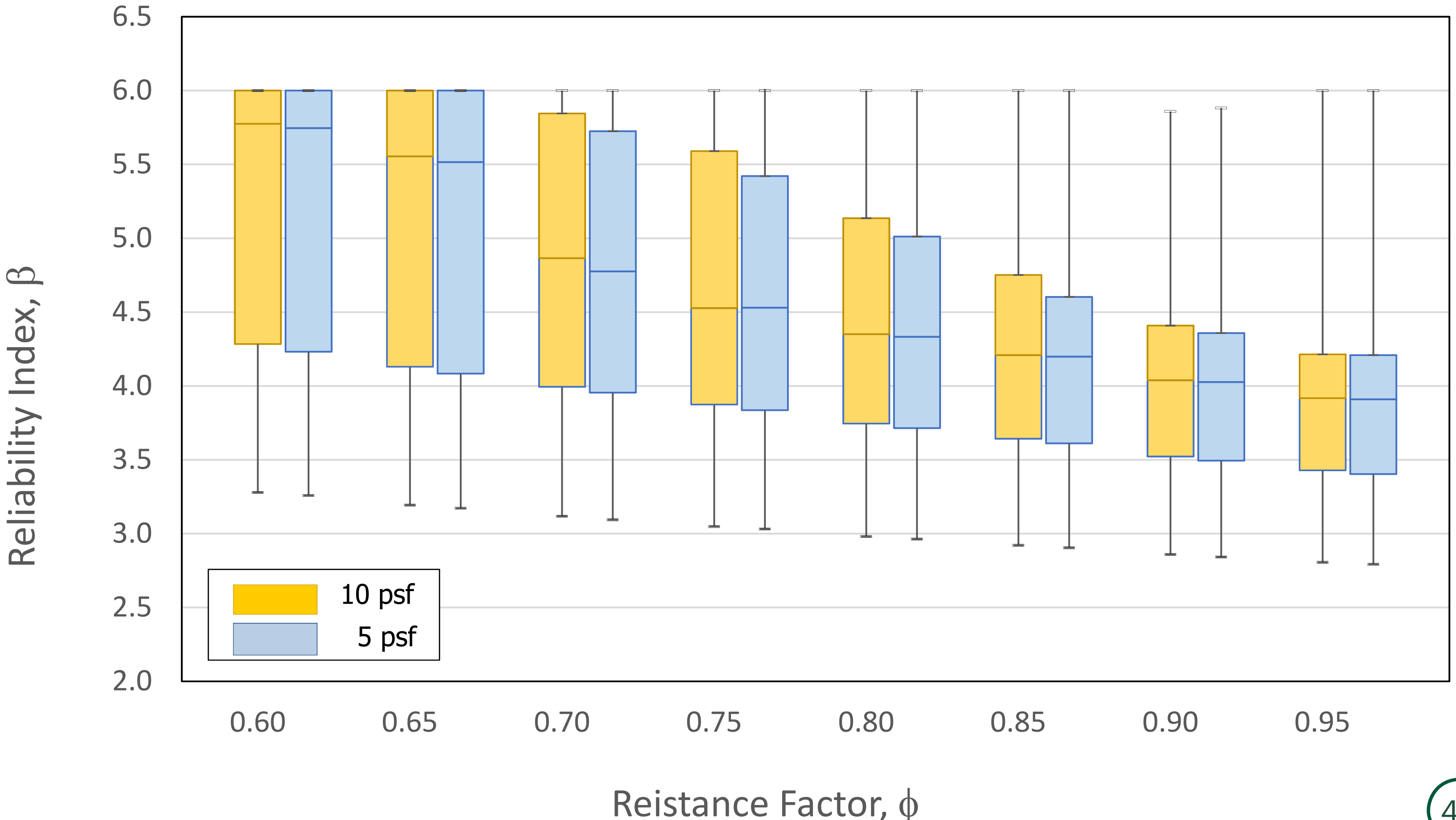
Reliability Index vs Resistance Factor (Anchorage)

Reliability Index for 10psf Dead Load

β = 6.0 chosen as P(f) = 0 (upper limit)



Box Plot for All Stations



Conclusions and Final Thoughts

Other Projects

Signs at K'esugi Ken Interpretive Center

Pros and Cons of RTA

- Advantages
  - Provides clear design values for code-reviewers
  - Provides confidence that design is consistent with failure probabilities of code provisions
  - Testing can be relatively economical
  - Does NOT require ICC-ES test report
  - Does NOT require ASTM test standard

- Disadvantages
  - Test procedures must be developed if none exist
  - Each configuration must be tested separately

References

Hamel, S., "*Testing and Analysis of Beam Pockets in Walls Made from Structurally Insulated Panels (SIPs)*", Report for Alaska Insulated Panels, August 2021.

Cox, N., and Hamel, S. "Static Modeling of Plywood Polyurethane Structural Insulated Panels in Bending", *ASCE Journal of Structural Engineering,* 147(2), November 2020.

Hamel, S.E., "*Structural Testing and Analysis of Plywood-Polyurethane Structurally Insulated Panels (SIPs)*", Report for Alaska Insulated Panels, March 5, 2018.

Meehleis, K., Folan, T., Hamel, S., Lang, R., Gienko, G., "Snow Load Calculations for Alaska using GHCN Data (1950-2017)." *Journal of Cold Regions Engineering*, 34 (3), September 2020.

Hamel, S. and Meehleis, K., "Alaska Snow Loads For The 2022 Update of ASCE 7," Anchorage, AK, 2019.

Nowak, A. and Collins, K., *Reliability of structures*, 2nd ed. Boca Raton, FL: CRC Press, 2012.

Ellingwood, B.R. and Galambos, T.V., "Probability-based Criteria for Structural Design," *Structural Safety*, vol. 1, no. 1969, pp. 283–288, 1983.

Ellingwood, B.R., MacGregor, J.G., Galambos, T.V., and Cornell, C.A., "Probability Based Load Criteria: Load Factors and Load Combinations.," *Journal of the Structural Division ASCE*, vol. 108, no. 5, pp. 978–997, 1982.

The Future…

Current and Ongoing Work

- Spread Footings
- Creep of Foundation Elements
- Seismic Evaluation

Proposals to Funding Agencies

- Wood Innovations – SIPs Technology that promotes Forest Products
- Charles Pankow Foundation – Creep and Seismic Evaluation of PU SIPs

Questions?