Reliability-based Calibration of Design Code for Concrete Structures (ACI 318)

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ACI 318 Code

Outline

- Objectives
- New material test data
- Resistance parameters
- Reliability analysis
- Resistance factors
- Further developments

DESIGN CODES HISTORICAL PERSPECTIVE

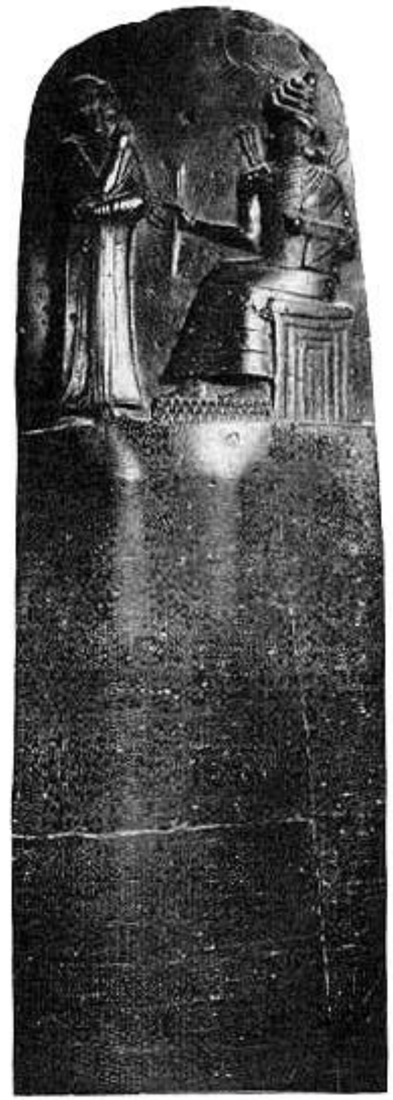
A. If a builder build a house for a man and do not make its construction firm and the house which he has built collapse and cause the death of the owner of the house – that builder shall be put to death.

B. If it cause the death of the son of the owner of the house – they shall put to death a son of that builder.

C. If it cause the death of a slave of the owner of the house – he shall give to the owner of the house a slave of equal value.

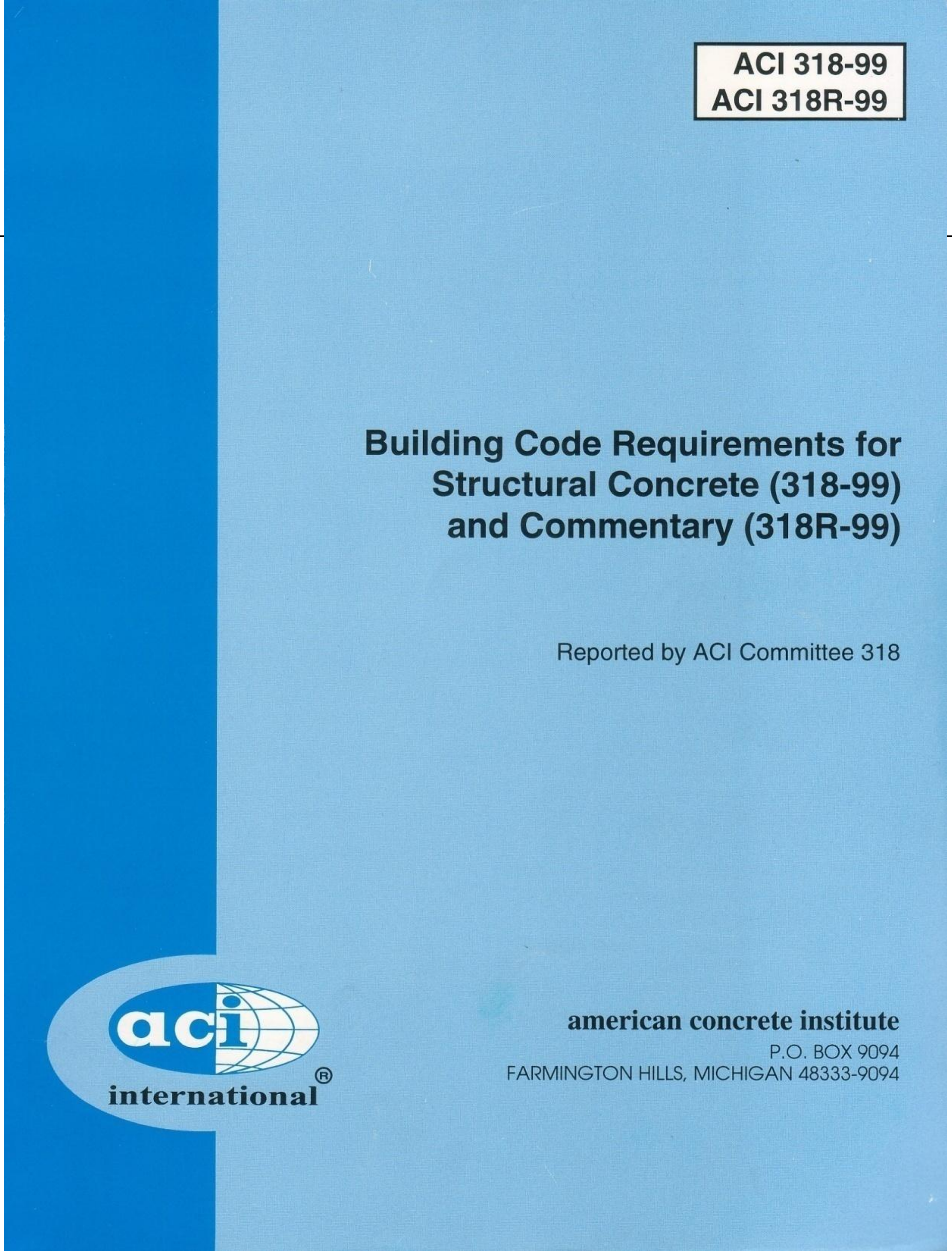
D. If it destroy property, he shall restore whatever it destroyed, and because he did not make the house which he built firm and it collapsed, he shall rebuild the house which collapsed at his own expense.

E. If a builder build a house for a man and do not make its construction meet the requirements and a wall fall in, that builder shall strengthen the wall at his own expense.



ACI 318 Code

- The basic document for design of concrete (R/C and P/C) buildings in USA
- ACI 318 specifies resistance factors and design resistance
- ACI 318 specifies load factors
- ACI 318 does not specify design load, reference is made to other codes


ACI 318-99
ACI 318R-99
Building Code Requirements for Structural Concrete (318-99) and Commentary (318R-99)
Reported by ACI Committee 318
aci
international
american concrete institute
P.O. BOX 9094
FARMINGTON HILLS, MICHIGAN 48333-9094

Why Calibration of ACI 318?

- Current load factors were adopted in 1950's
- Introduction of the new code with loads and load factors, ASCE 7 (American Society of Civil Engineers)
- Load factors specified in ASCE 7 are already adopted for steel design (AISC) and wood (NDS)
- Problems with mixed structures (steel and concrete)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ASCE STANDARD
ASCE/SEI 7-10
Minimum Design Loads for Buildings and Other Structures
This document uses both the International System of Units (SI) and customary units
ASCE
SEI
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Load factors specified by ACI 318 and ASCE 7

The design formula specified by ACI 318-99 Code

$1.4\ D + 1.7\ L < \phi\ R$

$0.75\ (1.4\ D + 1.7\ L + 1.7\ W) < \phi\ R$

$0.9\ D + 1.3\ W < \phi\ R$

$0.75\ (1.4\ D + 1.7\ L + 1.87\ E) < \phi\ R$

The design formula specified by ASCE-7 Standard

$1.4\ D < \phi\ R$

$1.2\ D + 1.6\ L < \phi\ R$

$1.2\ D + 1.6\ L + 0.5\ S < \phi\ R$

$1.2\ D + 0.5\ L + 1.6\ S < \phi\ R$

$1.2\ D + 1.6\ W + 0.5\ L + 0.5\ S < \phi\ R$

$1.2\ D + 1.0\ E + 0.5\ L + 0.2\ S < \phi\ R$

$0.9\ D - (1.6\ W \text{ or } 1.0\ E) < \phi\ R$

Objectives of Calibration of ACI 318

- Determine resistance factors, ϕ, corresponding to the new load factors (ASCE 7)
- Reliability of the designed structures cannot be less the predetermined minimum level
- Maintain a competitive position of concrete structures
- If needed, identify the need for changes of load factors in the ASCE 7

Code Calibration Procedure

- Selection of representative structural types and materials
- Formulate limit state functions, identify load and resistance parameters
- Develop statistical models for load and resistance parameters
- Develop the reliability analysis procedure
- Select the target reliability level(s)
- Determine load and resistance factors

Considered Structural Components

- Beams (reinforced concrete, prestressed concrete)
- Slabs (reinforced concrete, prestressed concrete)
- Columns (reinforced concrete, prestressed concrete, tied and spiral, axial and eccentric)
- Plain concrete

Considered Load Components

- D = dead load
- L = live load
- S = snow
- W = wind
- E = earthquake
- Load combinations

Assumed Statistical Data

- Dead load

  λ = 1.03-1.05, V = 0.08-0.10
- Live load

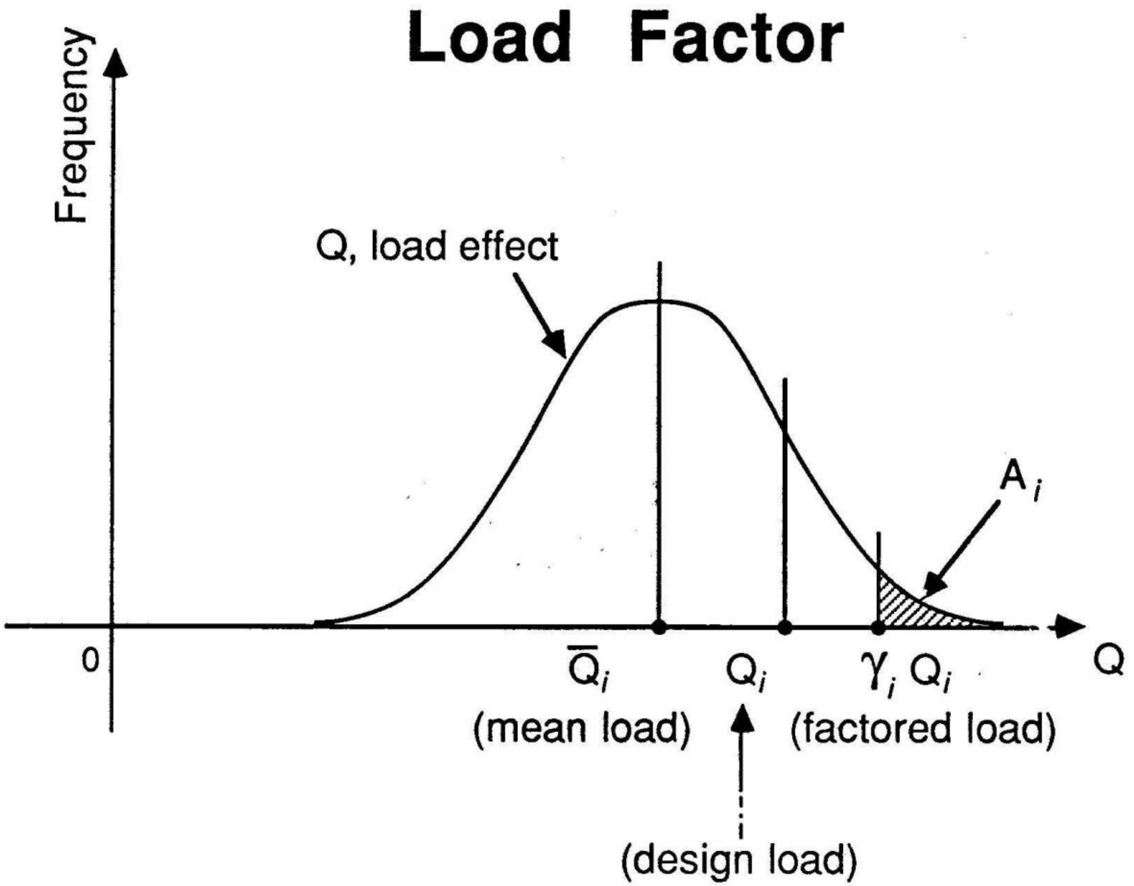
  λ = 1.00, V = 0.20
- Wind

  λ = 0.80, V = 0.35
- Snow

  λ = 0.80, V = 0.25
- Earthquake

  λ = 0.65, V = 0.55

Load Factor


Load Factor
Frequency
Q, load effect
A_i
0
$\bar{Q}_i$
(mean load)
Q_i
$\gamma_i\, Q_i$
(factored load)
Q
(design load)

Considered Materials

- Concrete (cast-in-place and precast)
  - Ordinary concrete
  - Light weight concrete
  - High strength concrete ($f'_c \geq 45$ MPa)
- Reinforcing steel bars
- Prestressing steel strands

Considered Cases

- Old
  - Statistical data for materials from 1970's
  - Design according to ACI 318-99
- New
  - Statistical data for materials from 2001-05
  - Design according to proposed ACI 318

Objectives

- Update the materials strength models using new statistical data
- Update the resistance models for reliability analysis
- Calculate reliability indices for components designed using ACI 318-12
- Provide a basis for selection of resistance factors

Parameters of Resistance

- Material : uncertainty in the strength of material, modulus of elasticity, cracking stresses, and chemical composition.
- Fabrication : uncertainty in the overall dimensions of the component which can affect the cross-section area, moment of inertia, and section modulus.
- Analysis : uncertainty resulting from approximate methods of analysis and idealized stress/strain distribution models.

Parameters of Resistance

$$R = R_n \, M \, F \, P$$

where :

R_n = nominal value of resistance

M = material factor

F = fabrication factor

P = professional factor

Parameters of Resistance

- The mean value of R is

$$\mu_R = R_n \mu_M \mu_F \mu_P$$

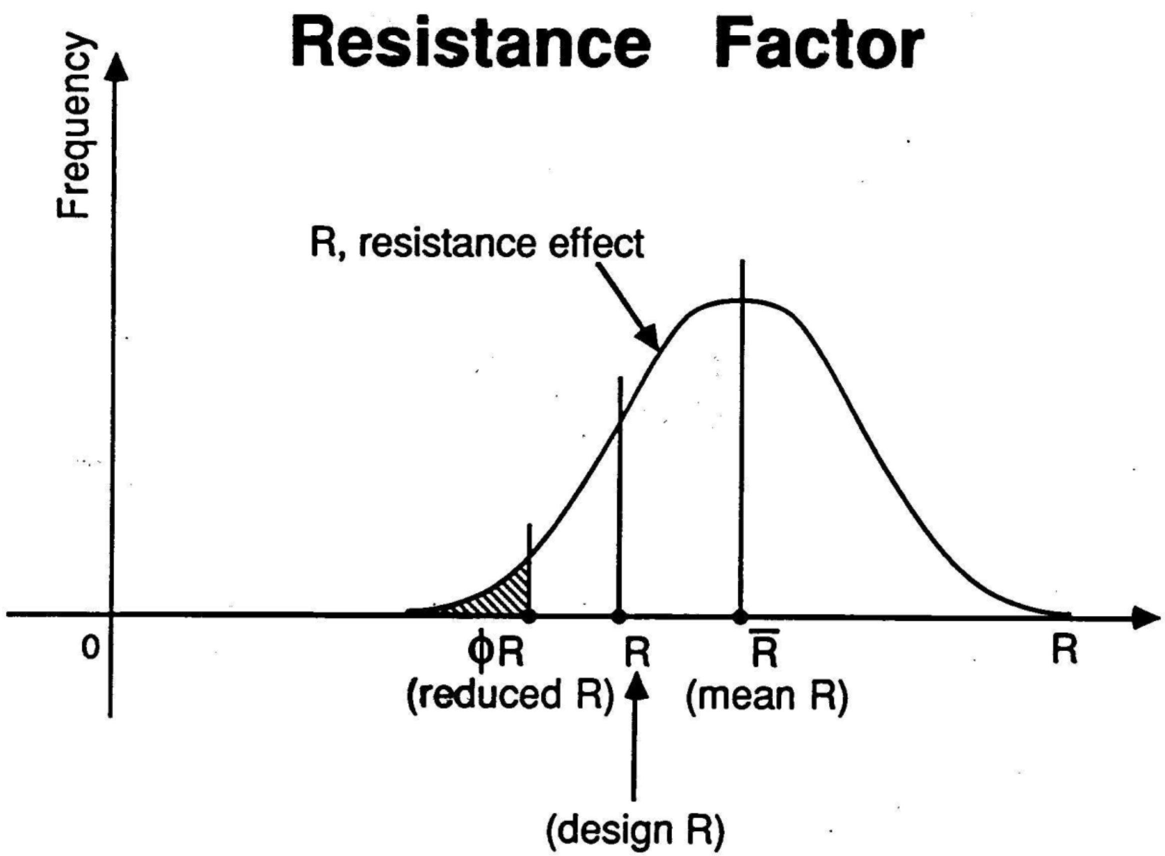
- Coefficient of variation

$$V_R = \sqrt{(V_M)^2 + (V_F)^2 + (V_P)^2}$$

- Bias factor

$$\lambda_R = \lambda_M \lambda_F \lambda_P$$

Resistance Factor



φ is calibrated to get $\beta = \beta_T$

Material Factor

- Available data-base from 1970’s (MacGregor)
- Concrete industry provided test results (2000-2001 and 2003), gathered for this calibration
- Code Calibration of ACI 318 (2005) is based on these recent test results

Concrete Strength

- Compressive strength - cylinders 6 x 12 in (150 x 300 mm)
- Mostly 28 day strength, for precast concrete also 56 day strength


Holcim
3/15
1/7 +10
2/13 +10
2/8


34
MAX PLATEN

Results of Material Tests

- Cumulative distribution functions (CDF)
- For an easier interpretation of the results, CDF's are plotted on the normal probability paper
- CDF of a normal random variable is represented by a straight line
- Any straight line on the normal probability paper represents a normal CDF

Strength of Ordinary Concrete

Ready mix concrete

3,000 psi (21 MPa)
3,500 psi (24 MPa)
4,000 psi (28 MPa)
4,500 psi (31 MPa)
5,000 psi (35 MPa)
6,000 psi (42 MPa)

Plant-cast concrete

5,000 psi (35 MPa)
5,500 psi (38 MPa)
6,000 psi (42 MPa)
6,500 psi (45 MPa)

Strength of Concrete

Light-weight concrete

3,000 psi (21 MPa)
3,500 psi (24 MPa)
4,000 psi (28 MPa)
5,000 psi (35 MPa)

High strength concrete

7,000 psi (49 MPa)
8,000 psi (56 MPa)
9,000 psi (62 MPa)
10,000 psi (70 MPa)
12,000 psi (84 MPa)

More Materials Data

- Compressive Strength of Ordinary Concrete, Ready mixed, fc’: 3,000 3,500 4,000 4,500 5,000 and 6,000psi (21-42 MPa)
- Yield Stress of Reinforcing Steel Bars, Grade 60 Bar Sizes: #3, #4, #5, #6, #7, #8, #9, #10, #11 and #14 (9.5mm – 44 mm)
- Breaking Stress of Prestressing Steel (7-wire strands), Grade 270 (1865 MPa), Nominal Diameters: 0.5 in and 0.6 in (12.5-15 mm)

Ordinary Concrete – Number of Samples

Specified Compressive Strength of Concrete f_c' [psi]:

Source:	3,000	3,500	4,000	4,500	5,000	6,000	Total:
1	334		316		138	130	
2			156				
3	96		71		84		
4	82				66		
5	52						
6			54				
7	36						
8			60				
9			50				
10					206		
11					294		
12	1046	21	27	839			
13	350		274	298	2		
14	203	54	269		263		
15	424	8	220	164	8		
16	562	339	584	52	100		
17	116			90			
18	173	6	99	36	133		
19	180	99	533	80	422		
20			18		6		
21	8			2			
22	78		26	12			
23	276			346			
24			27				
Total:	**4016**	**527**	**2784**	**1919**	**1722**	**130**	**11098**

Lightweight Concrete – Number of Samples

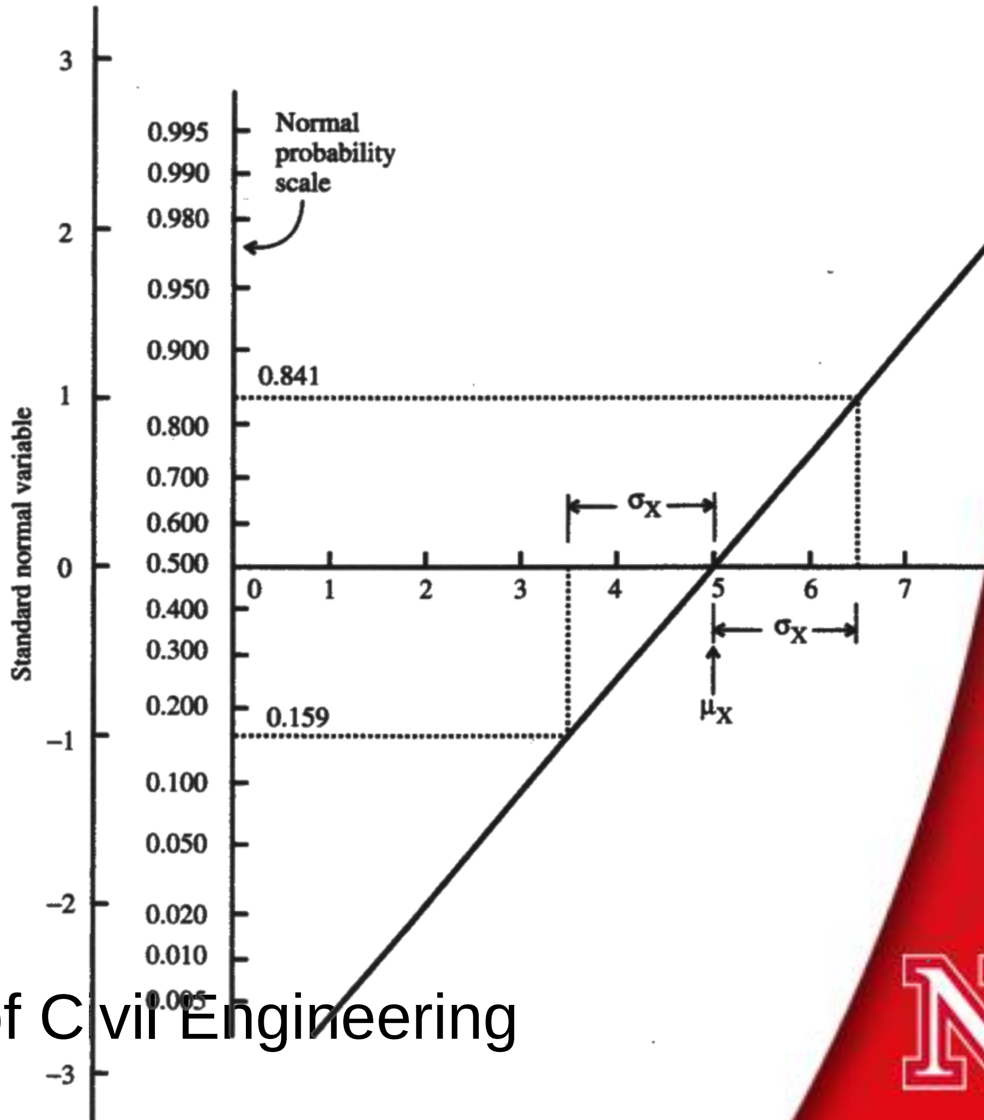
Source \ Strength, f_c'[psi]	3000	3500	4000	4500	5000	6000	6300	6800	7100
A					(286)				
B	282 (146)		180	1230 (752)	(79)	(517)			
C		417	542		(66)		876	392	517
D			334						
E			373						
F	61	132	246						
G	66	142	315		54 (52)				
H	100		82						
I*	100	42	140		368				
Total	**755**	**733**	**2212**	**1982**	**905**	**517**	**876**	**392**	**517**
Grand total	**8889**								

Presentation of Test Data

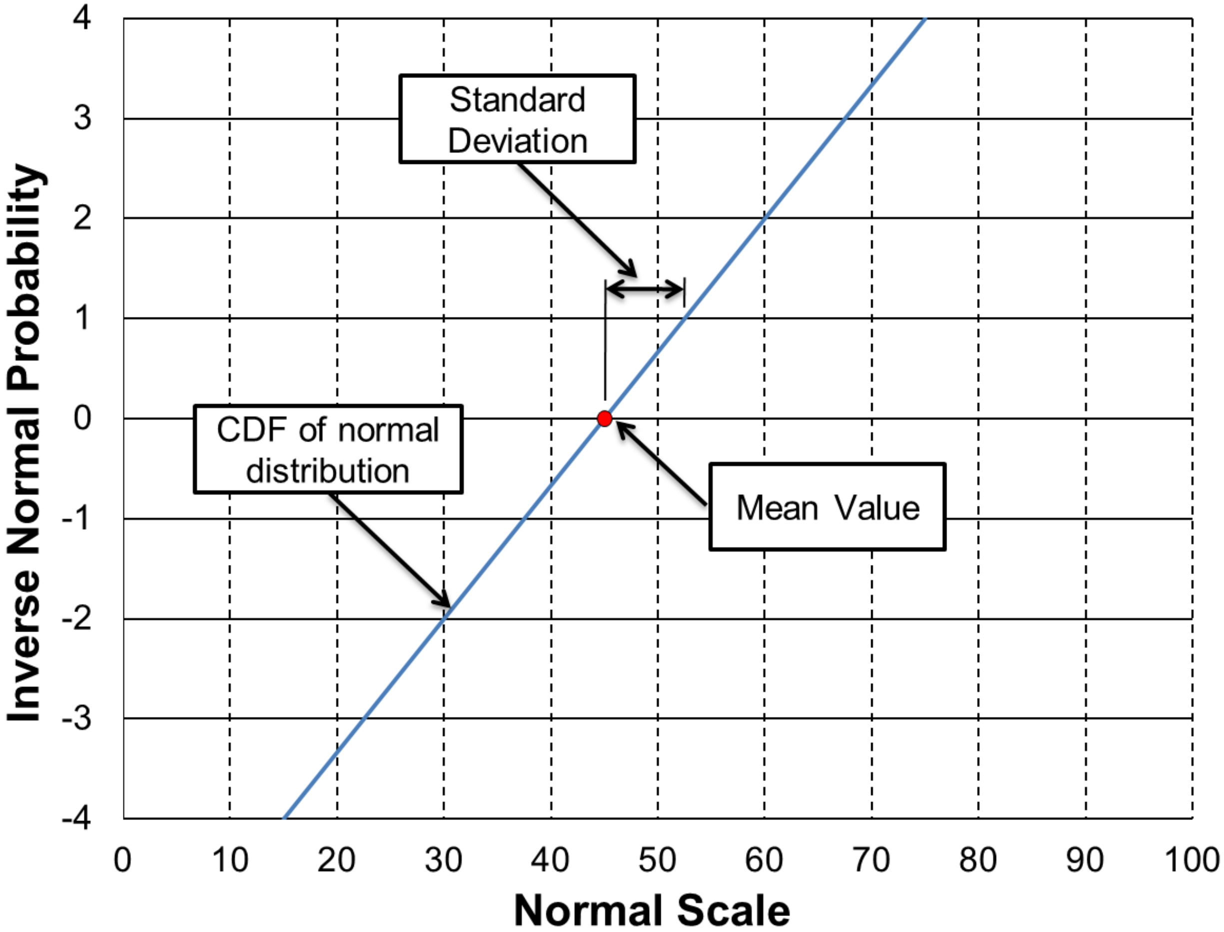
- Cumulative distribution functions (CDF) are plotted on the normal probability paper
- Vertical axis is the number of standard deviations from the mean value
- If CDF is close to a straight line, then the distribution is normal
- The mean and standard deviation can be read directly from the graph

Probability Paper

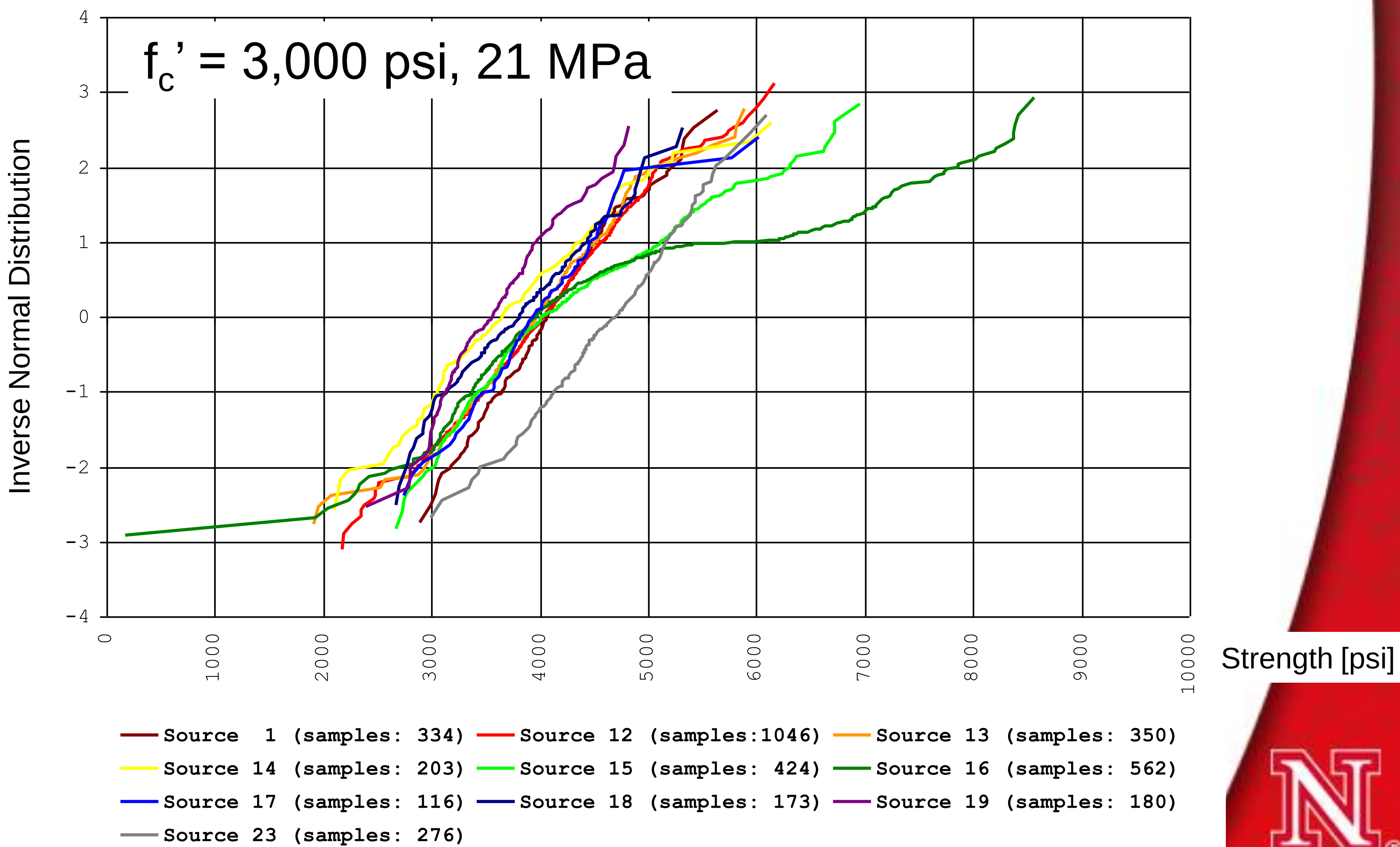
Data is plotted on the normal probability paper. A normal distribution function is represented by a straight line.



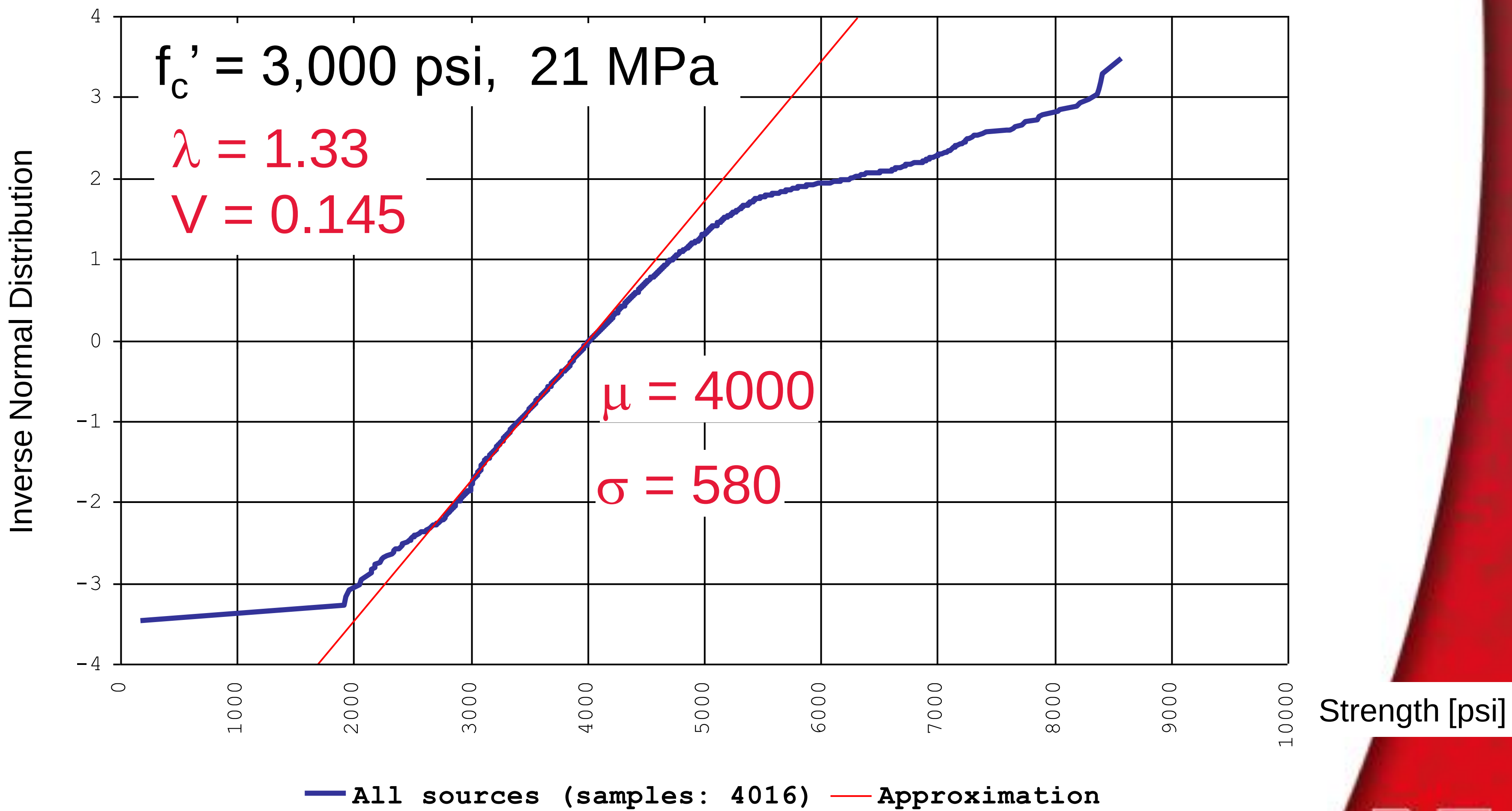
Probability Paper



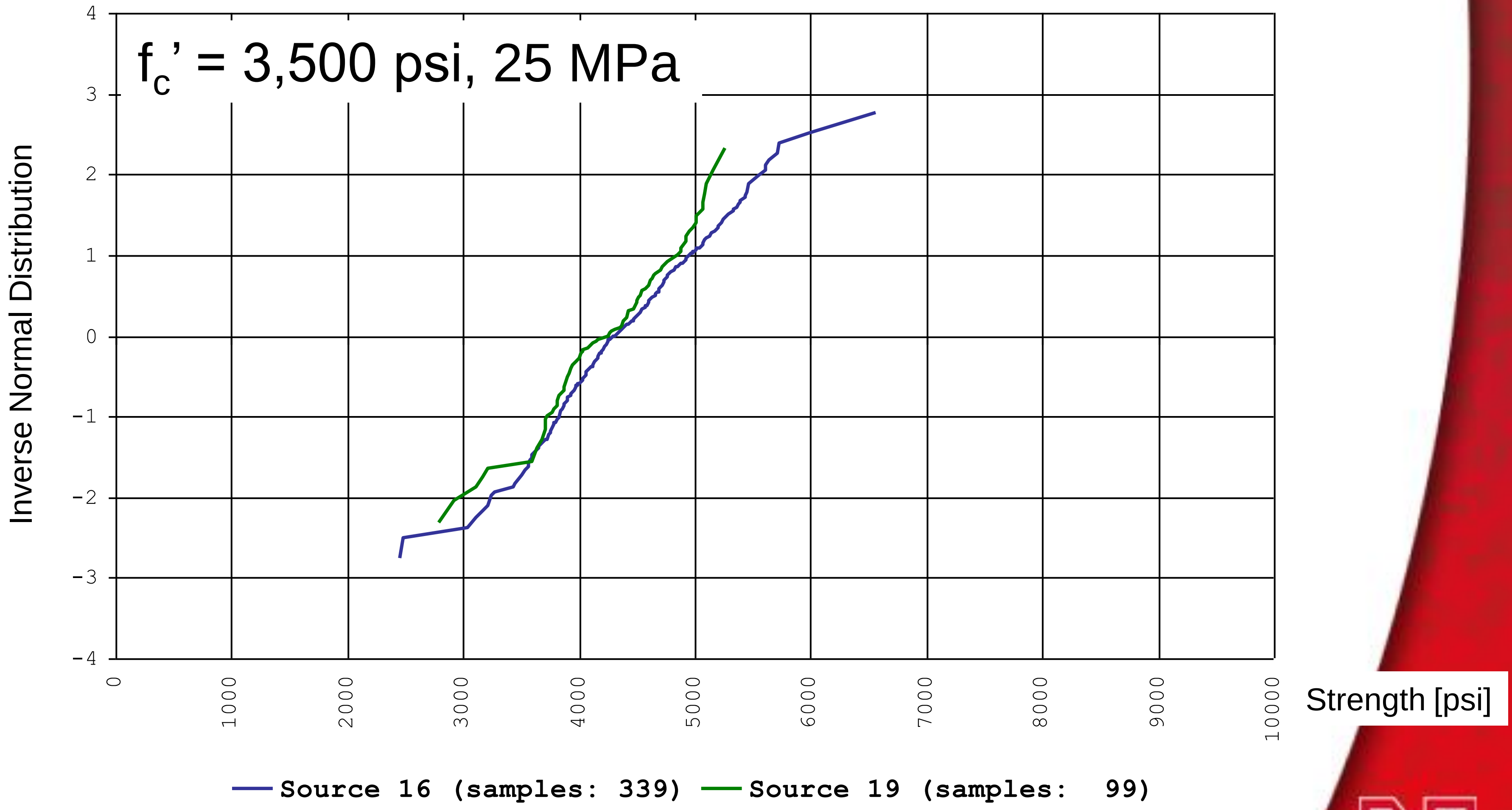
Ordinary Concrete – CDF of Strength



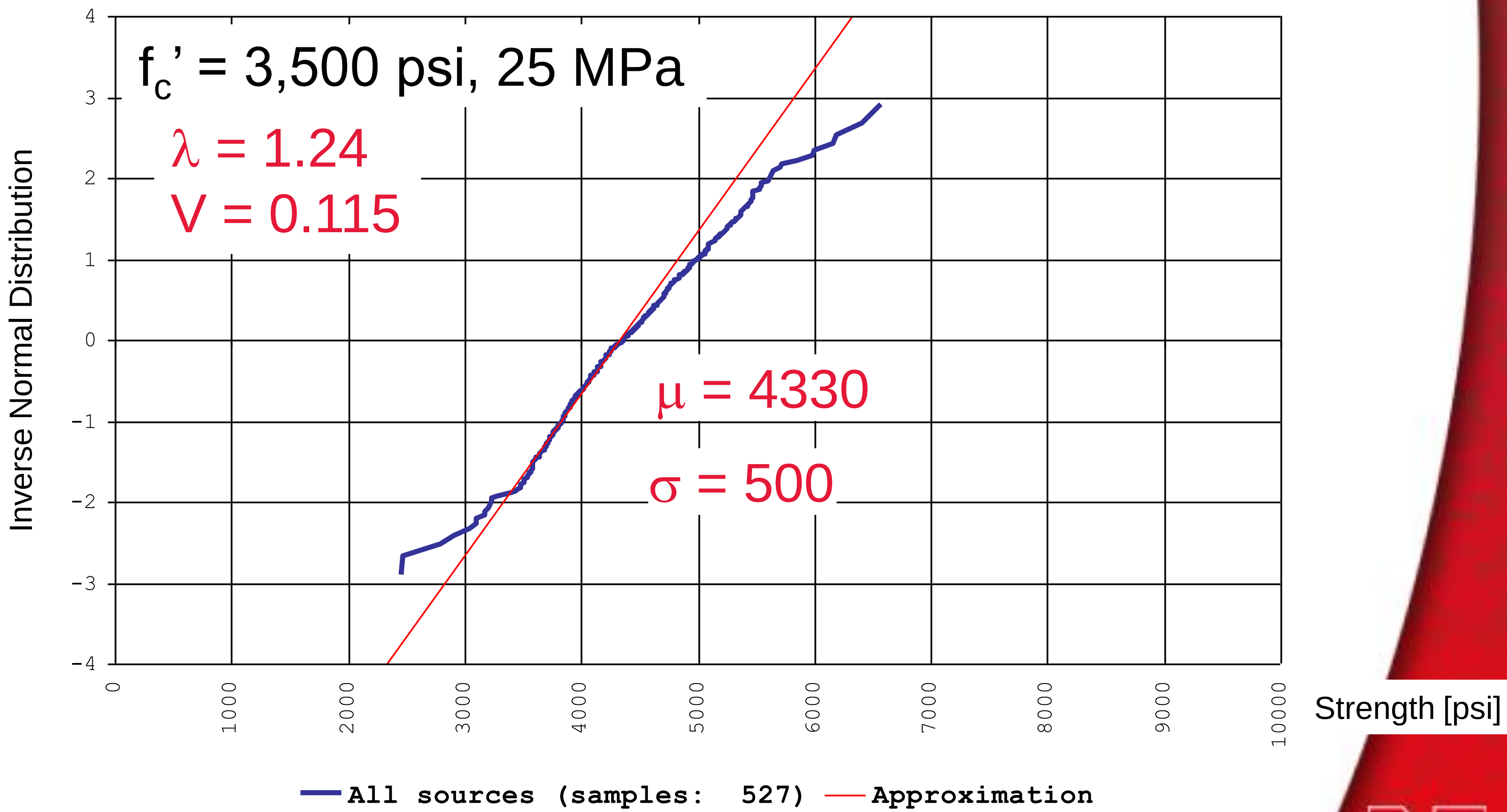
Ordinary Concrete – CDF of Strength



Ordinary Concrete – CDF of Strength



Ordinary Concrete – CDF of Strength



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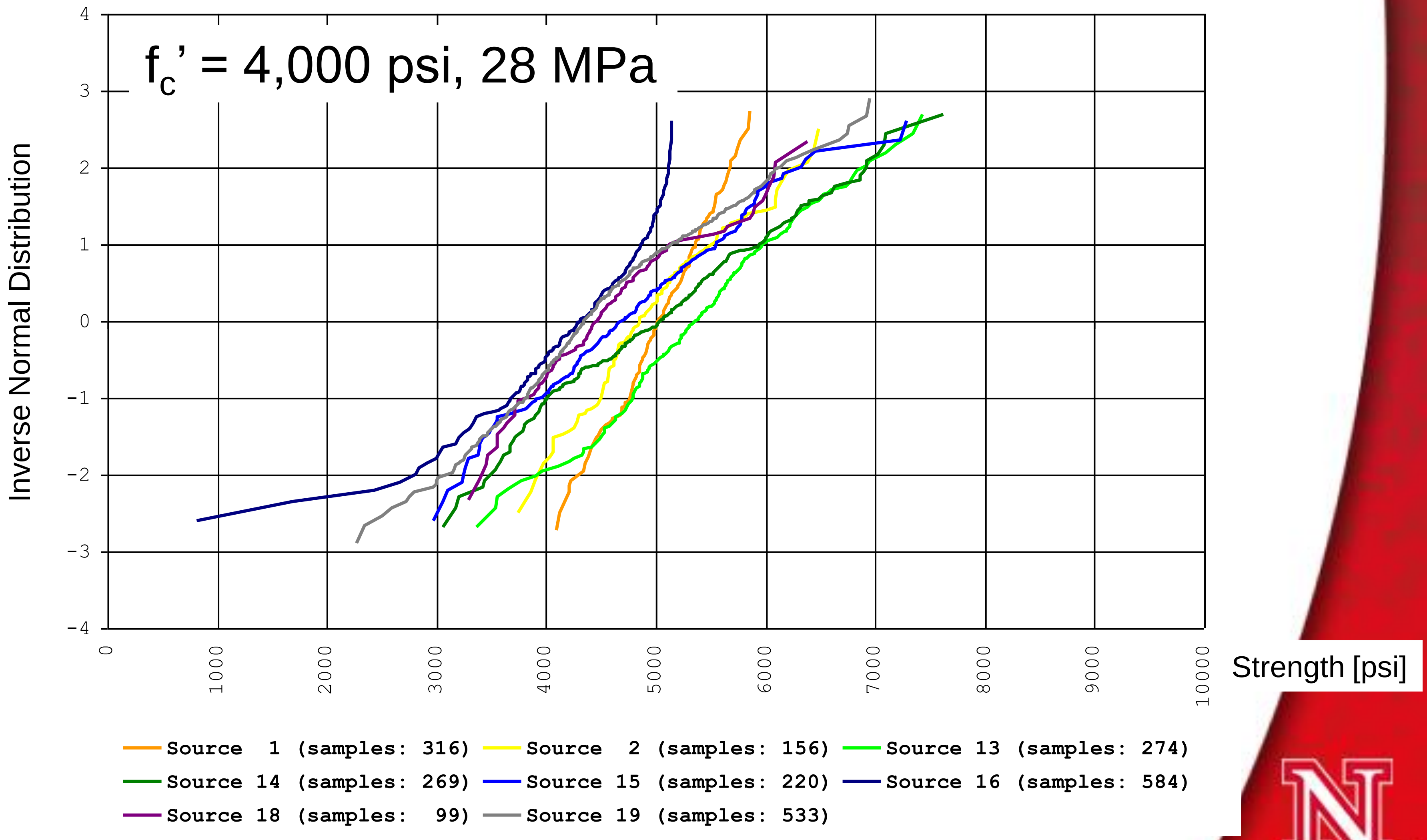

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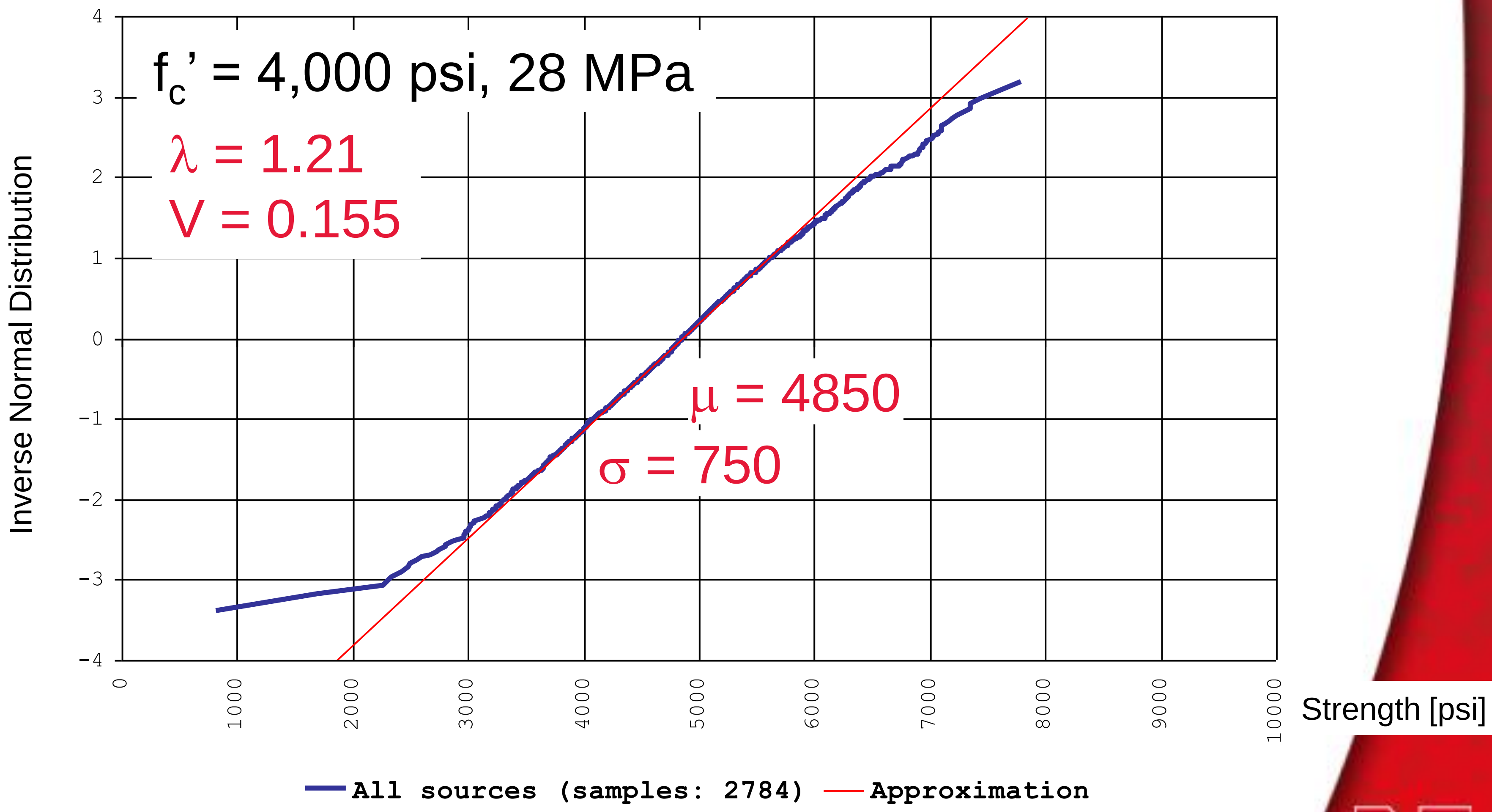

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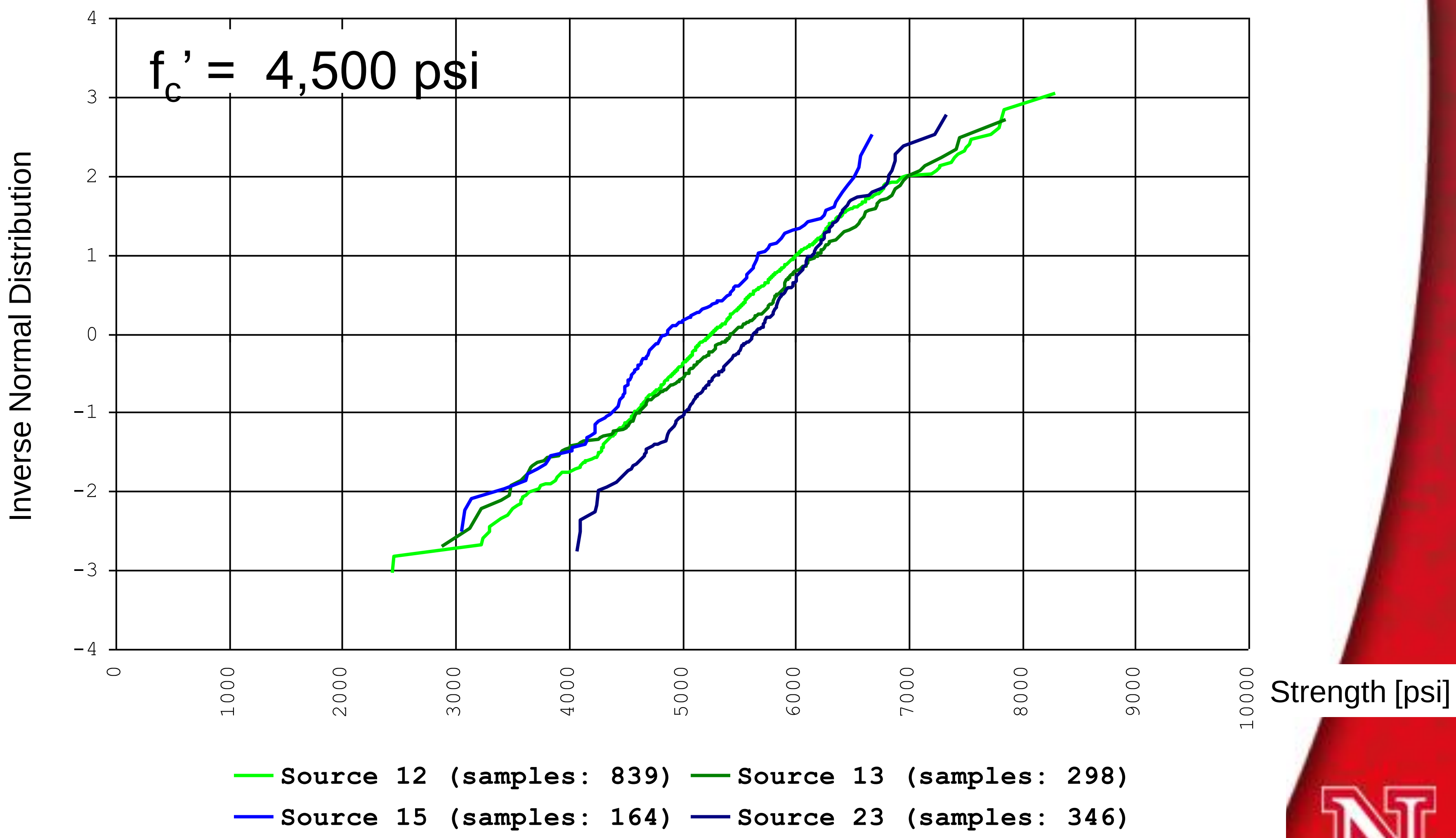
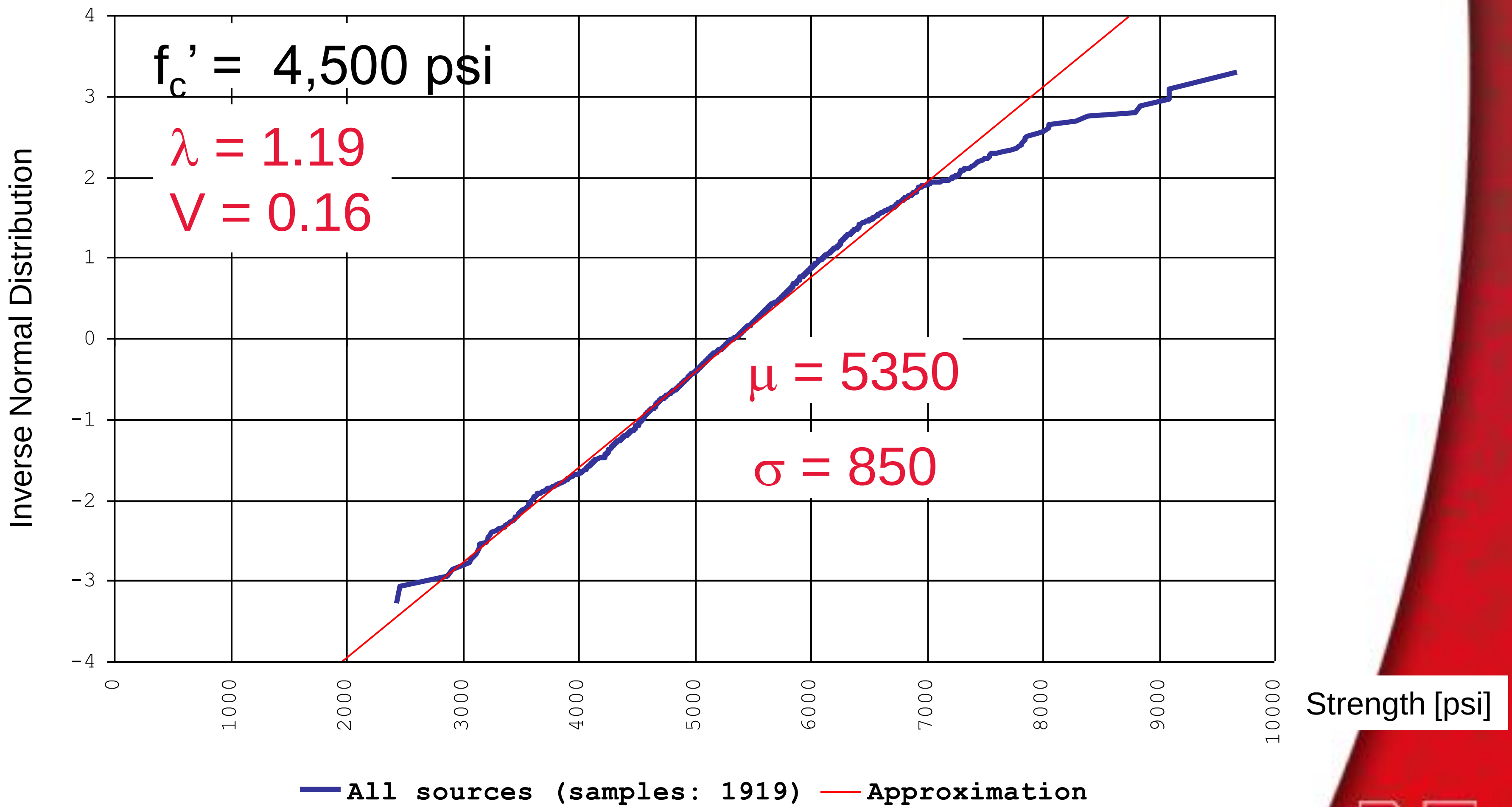


Ordinary Concrete – CDF of Strength



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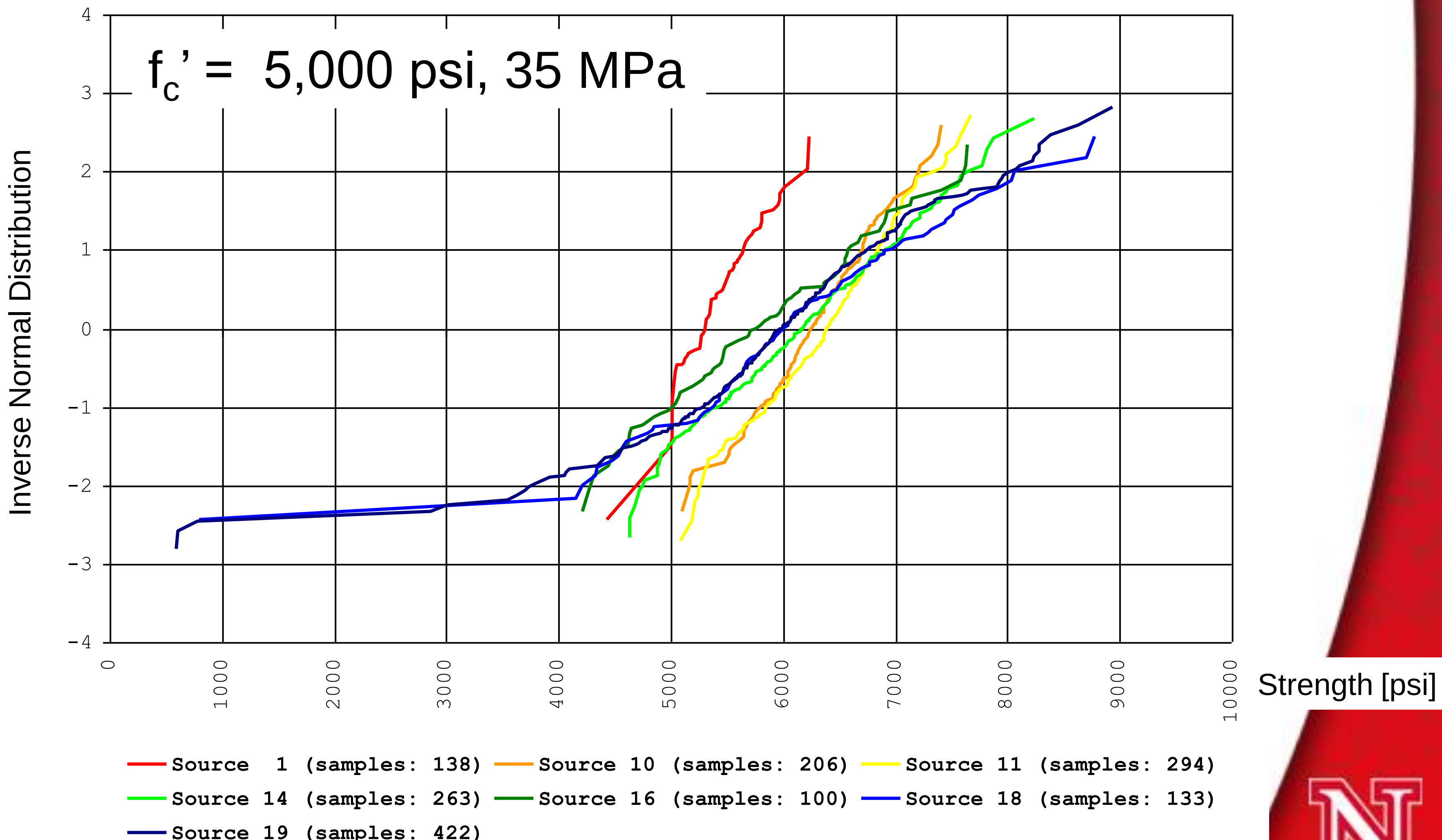
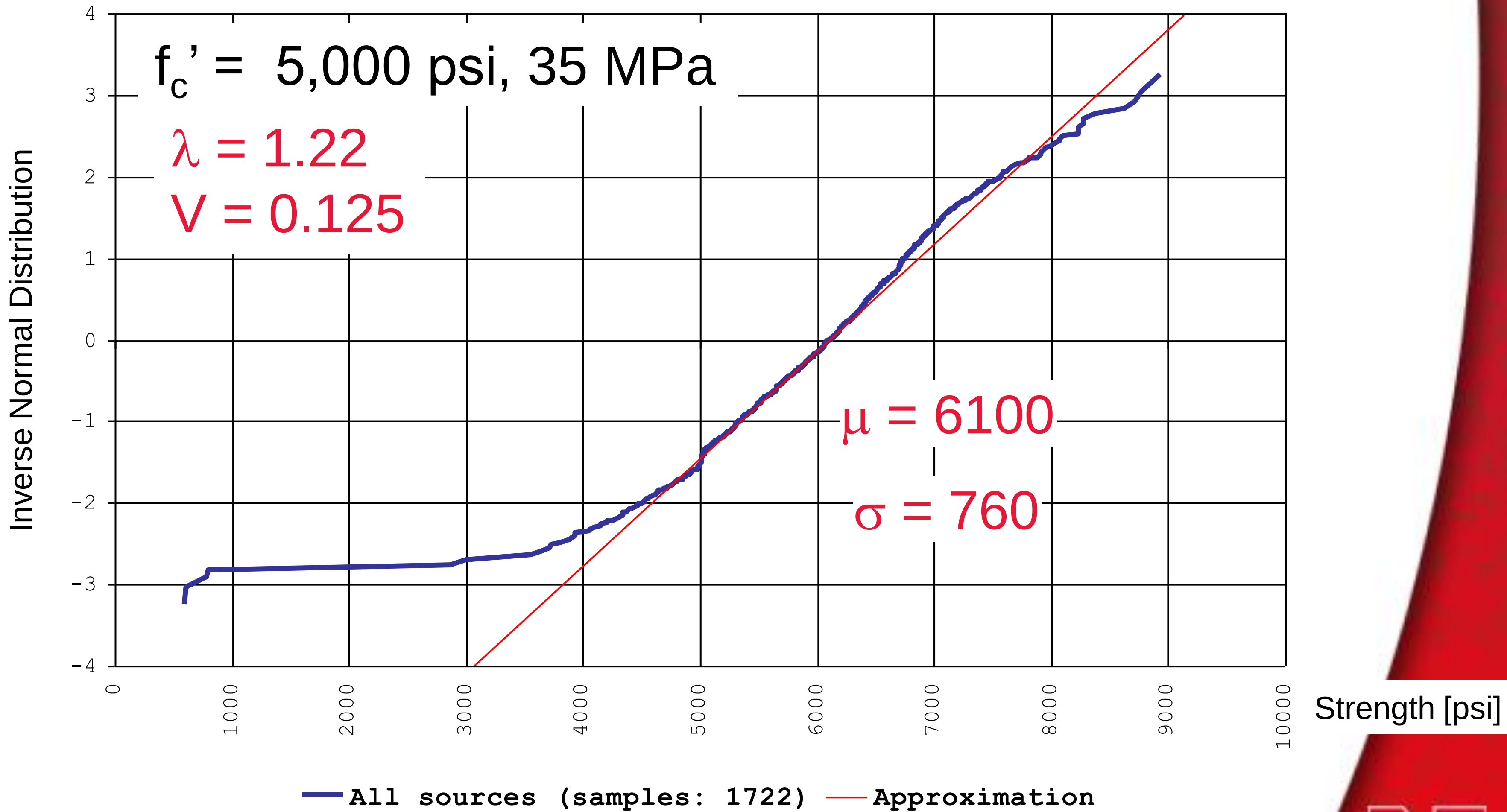
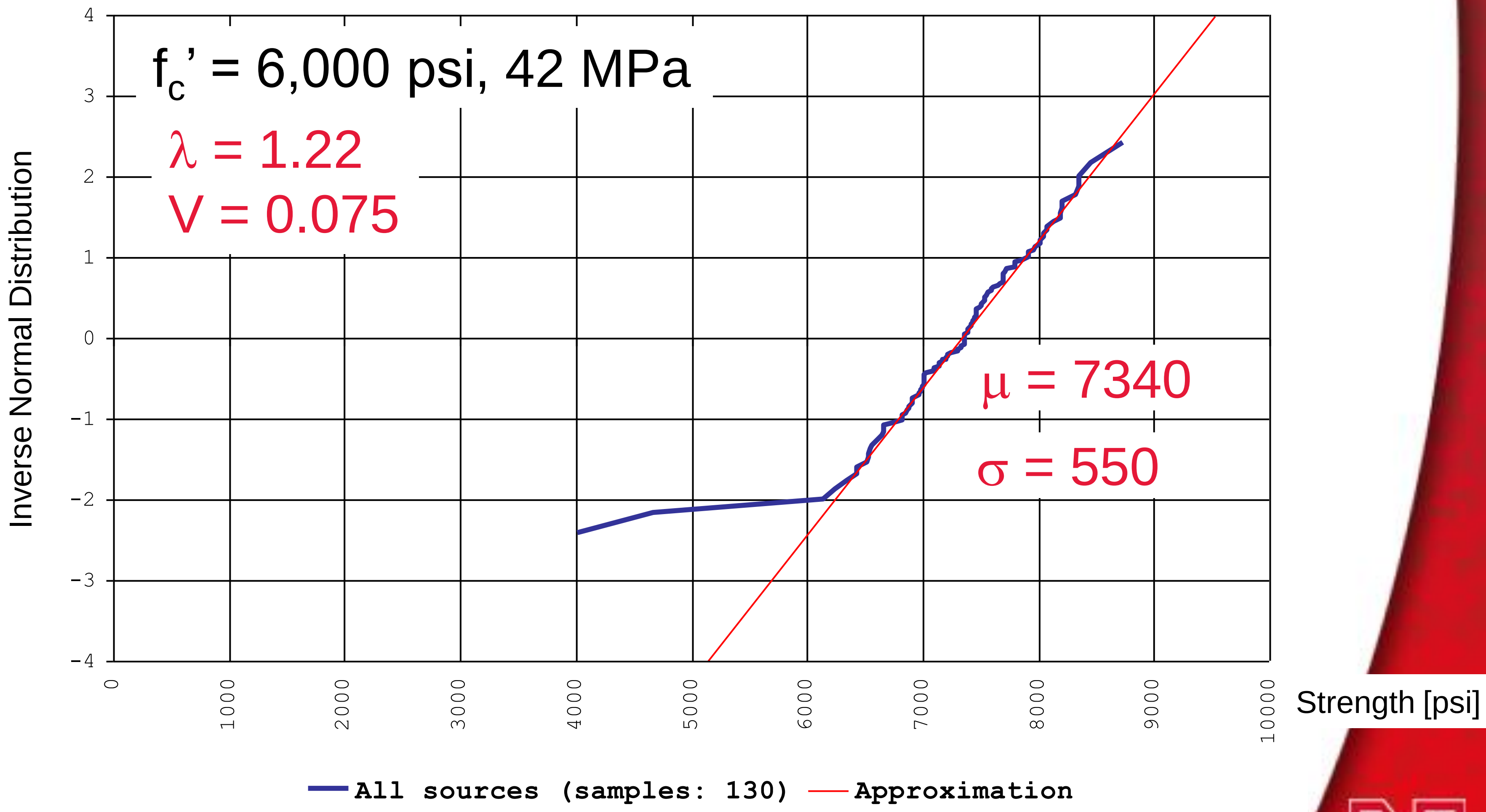


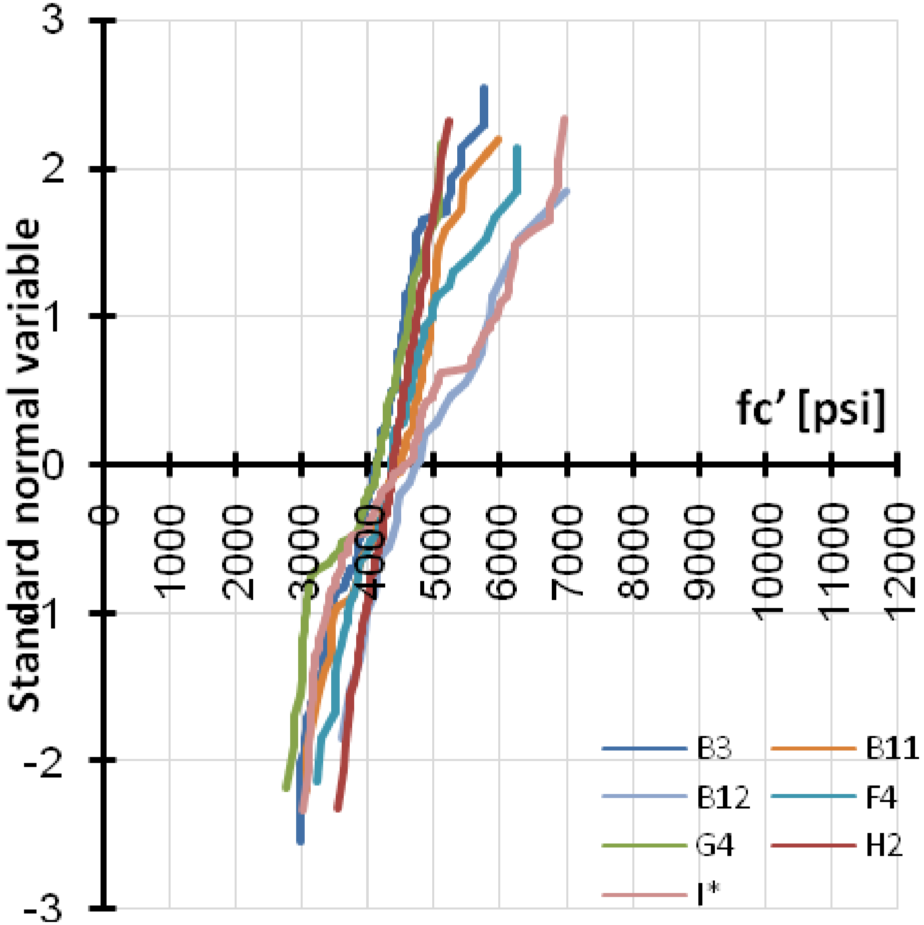
Ordinary Concrete – CDF of Strength

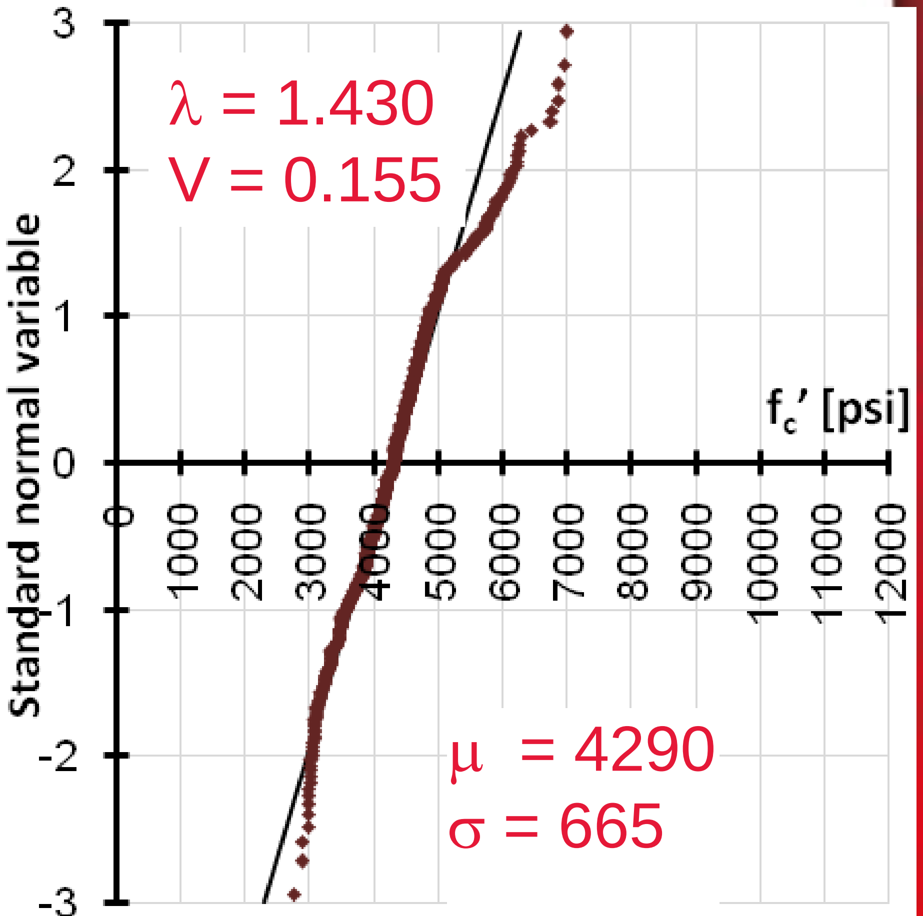


Ordinary Concrete – CDF of Strength



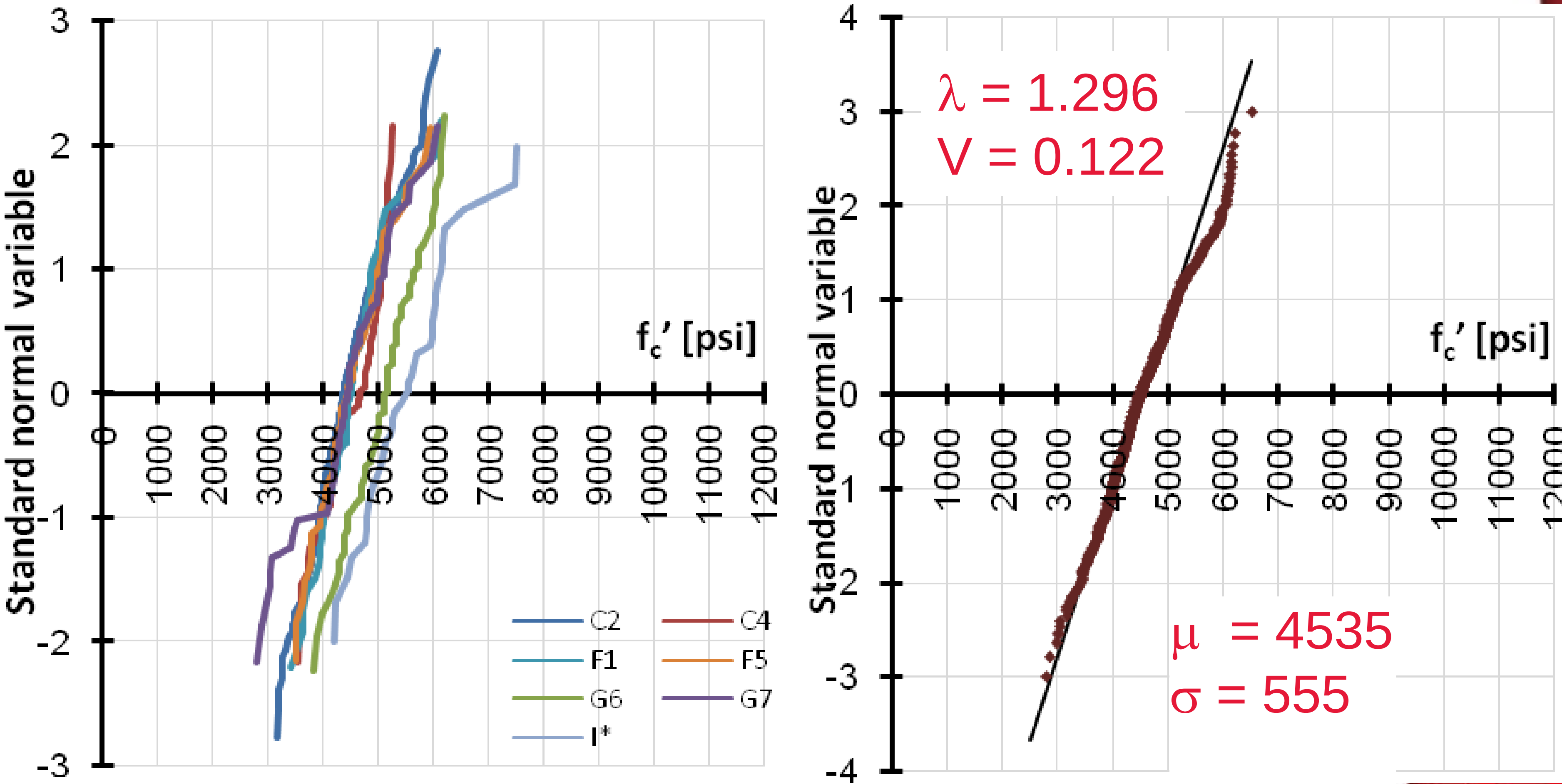
Lightweight Concrete – CDF of Strength





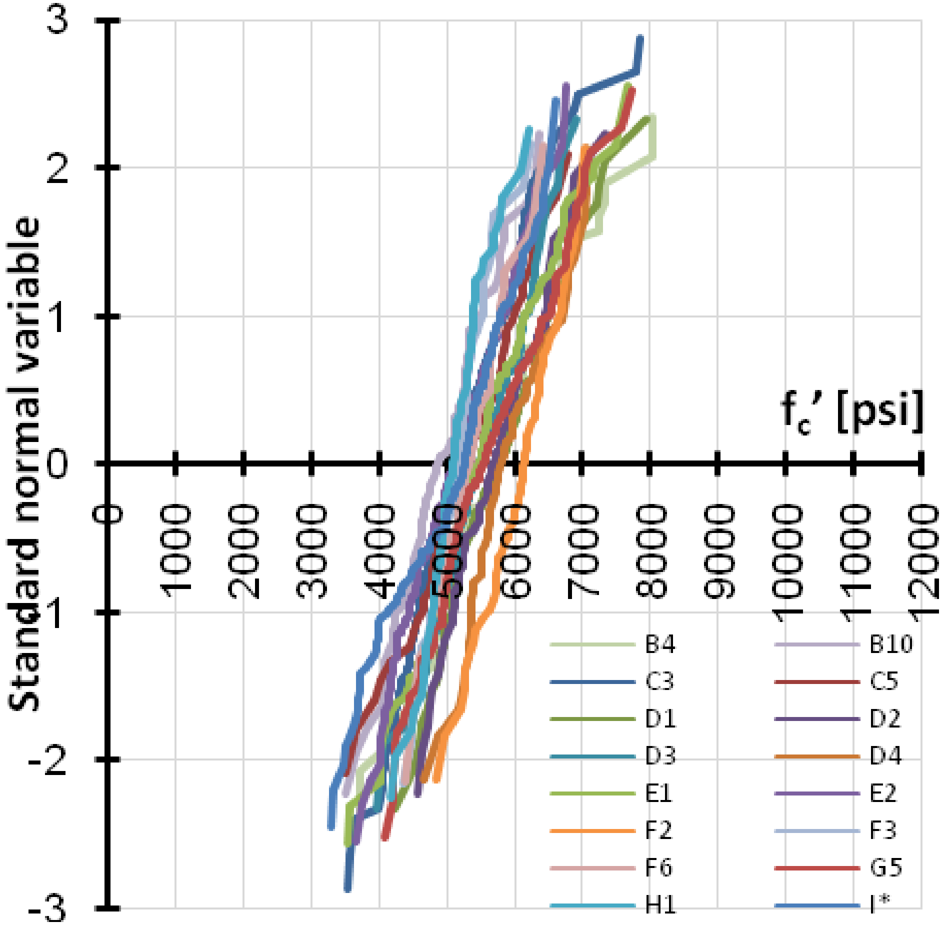
f_c'= 3000 psi, 21 MPa

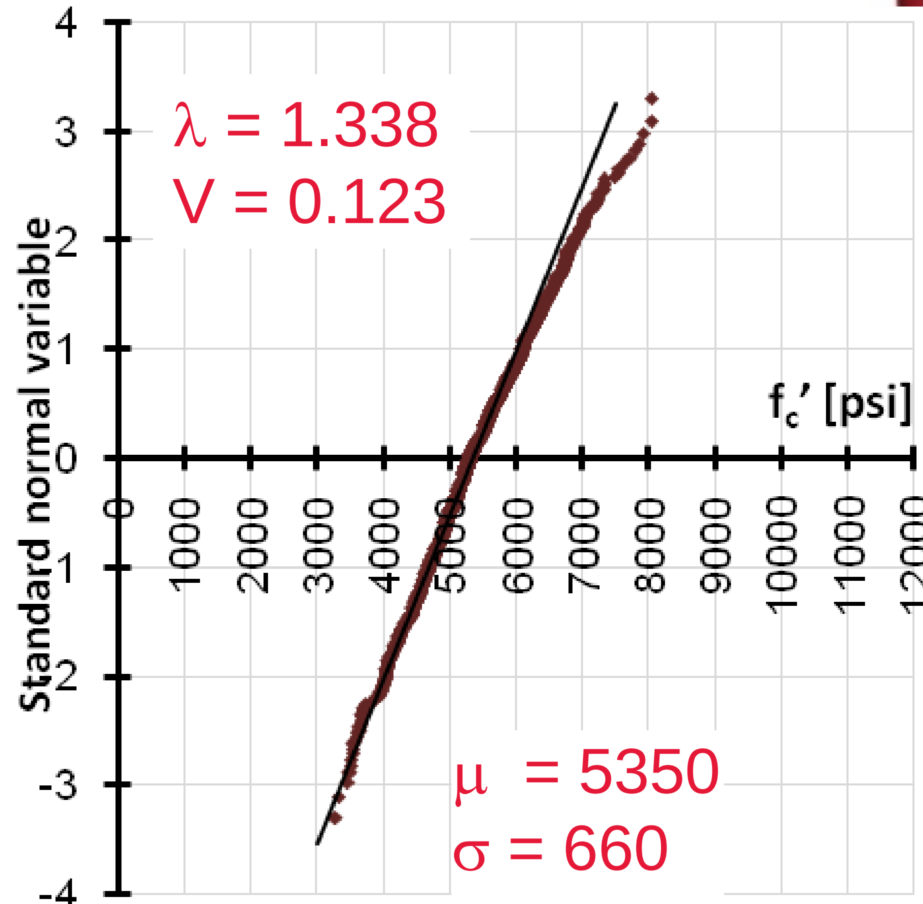
Lightweight Concrete – CDF of Strength



f_c'= 3500 psi, 25 MPa

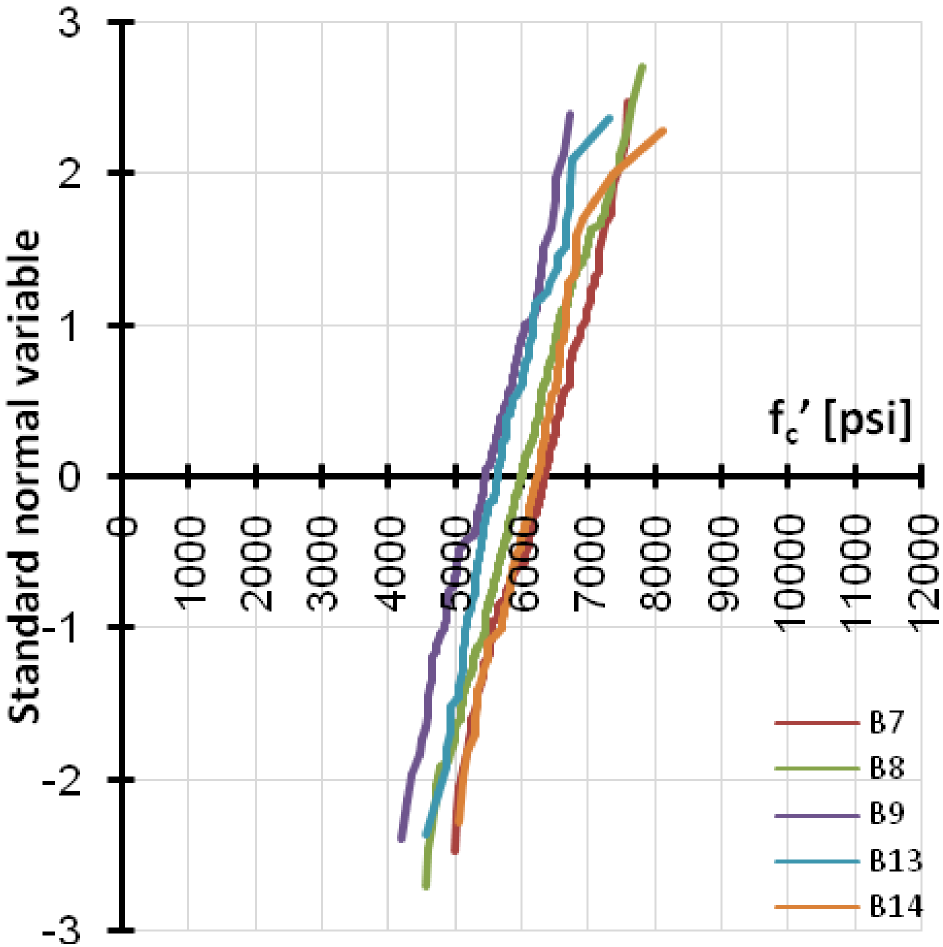
Lightweight Concrete – CDF of Strength

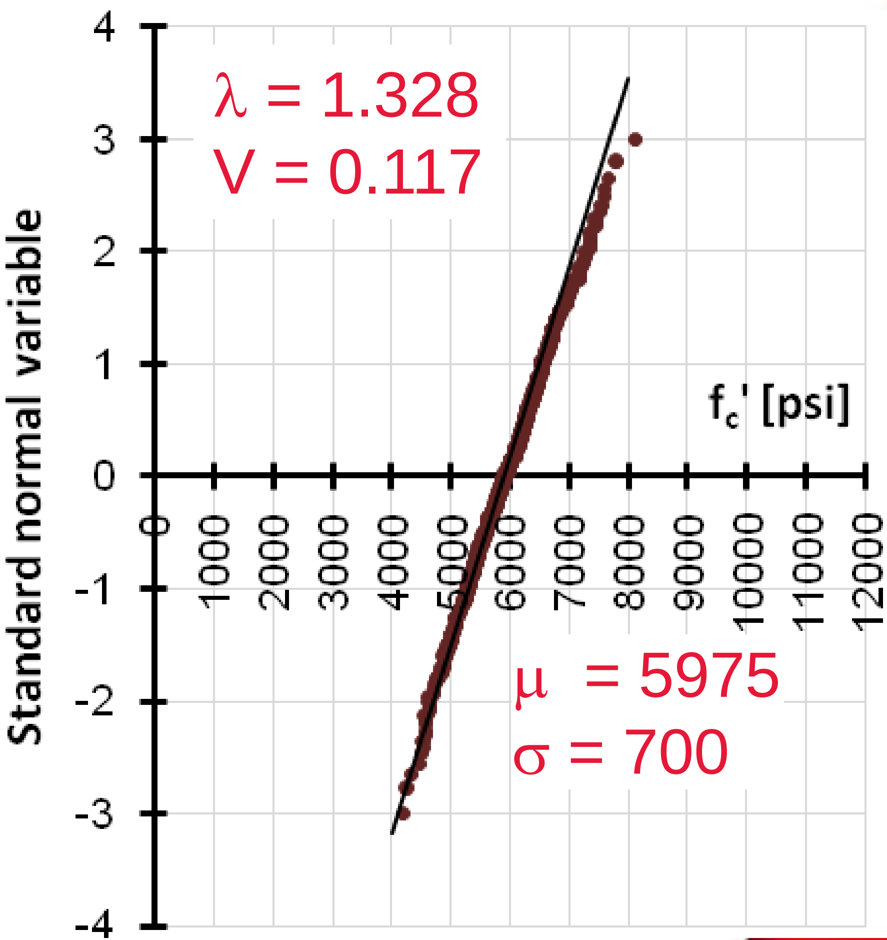




f_c'= 4000 psi, 28 MPa

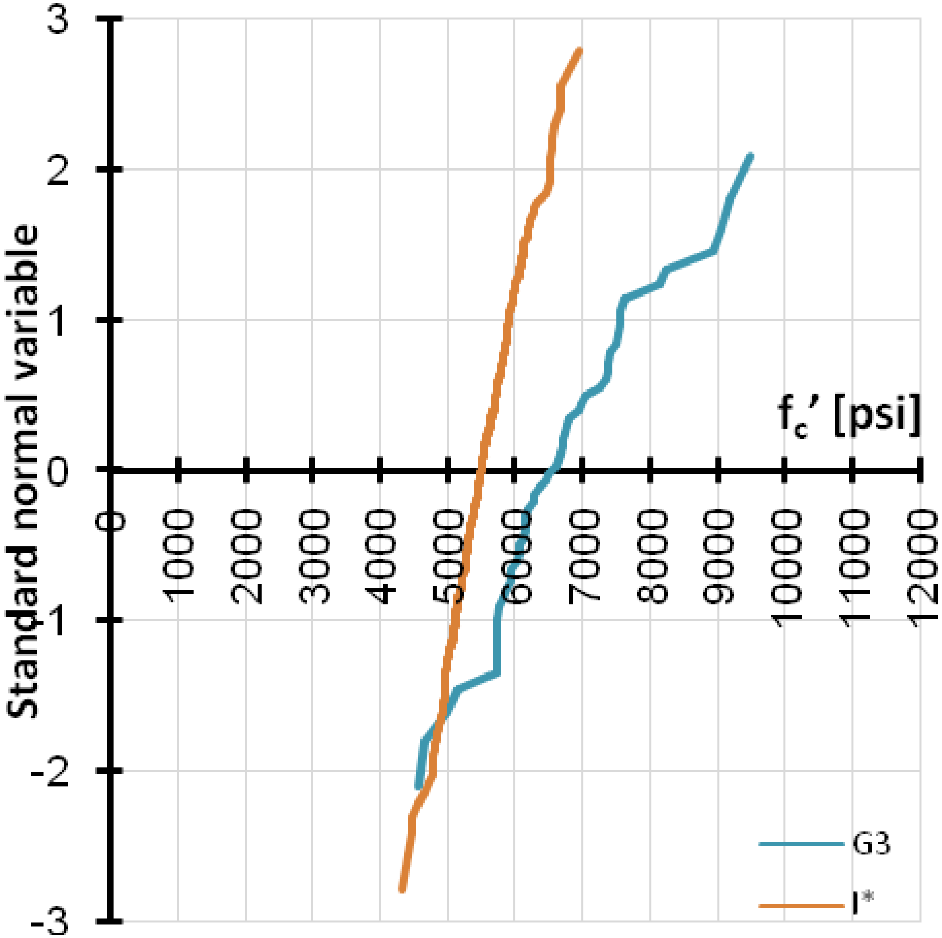
Lightweight Concrete – CDF of Strength

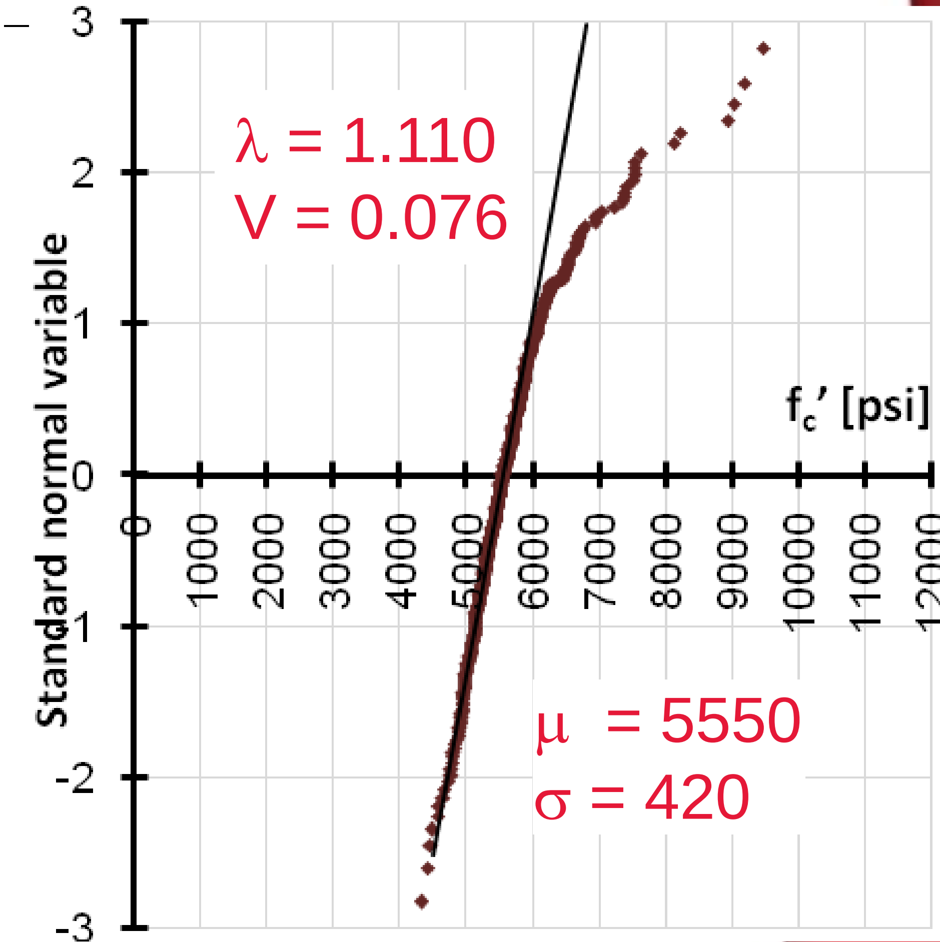




f_c'= 4500 psi , 32 MPa

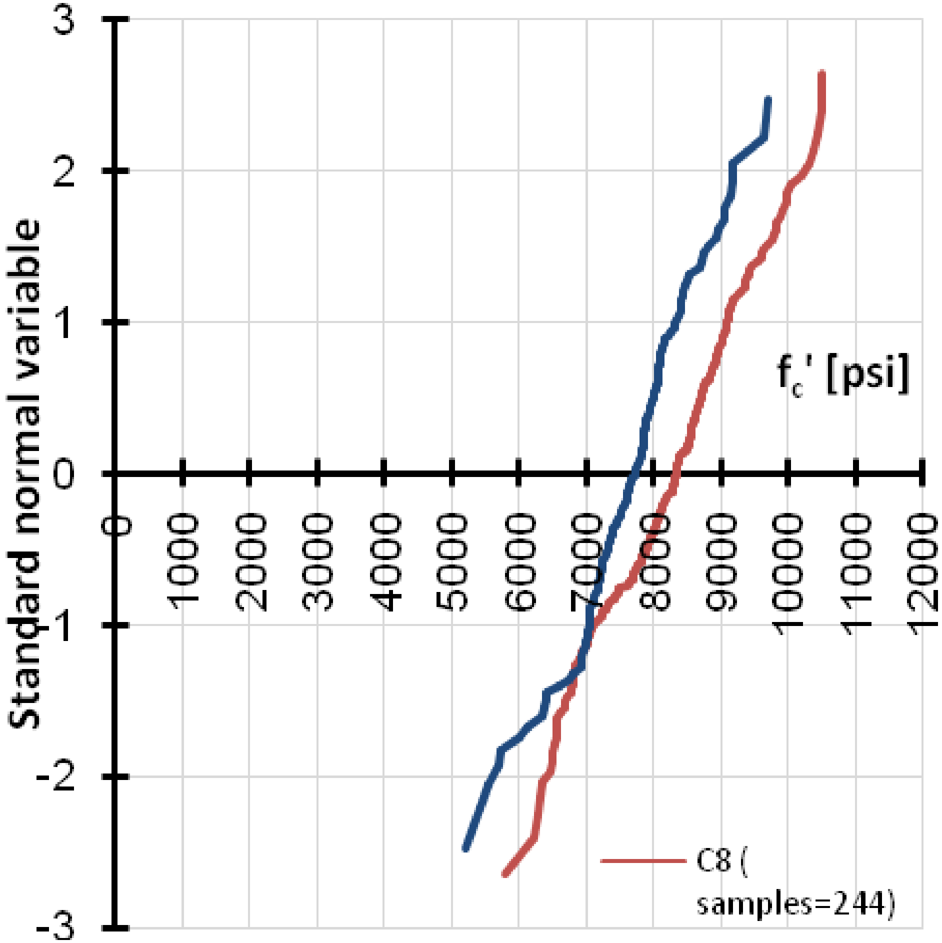
Lightweight Concrete – CDF of Strength

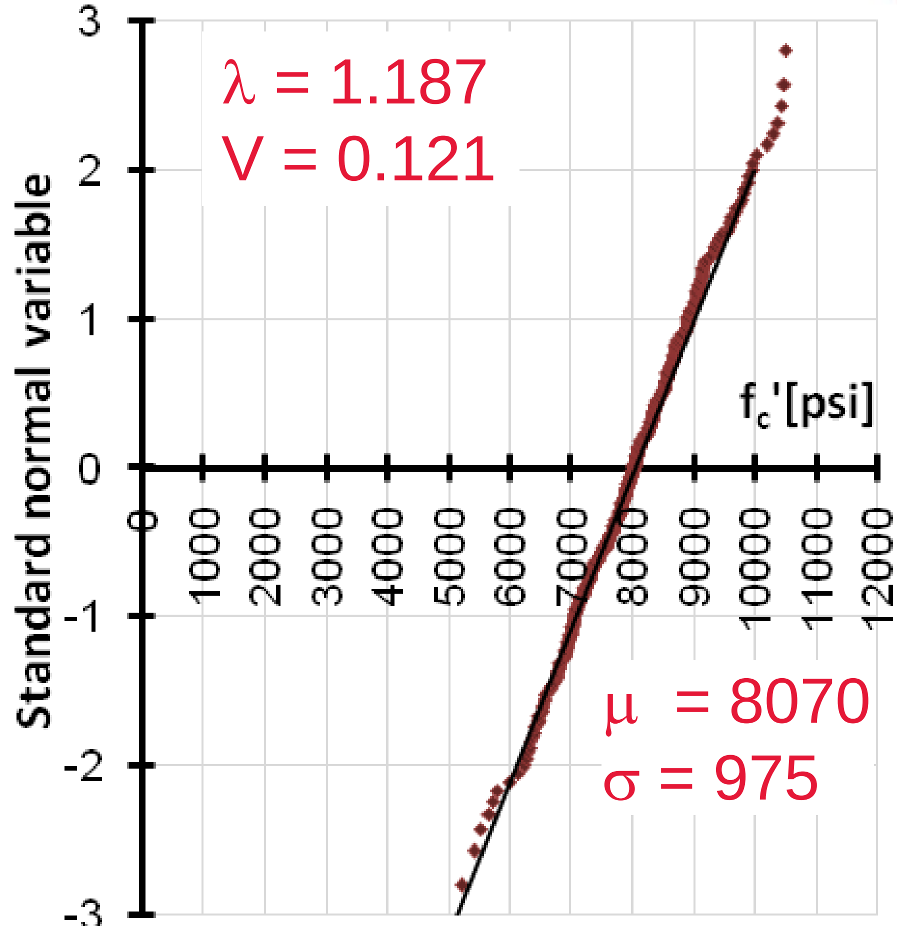




f_c'= 5000 psi , 35 MPa

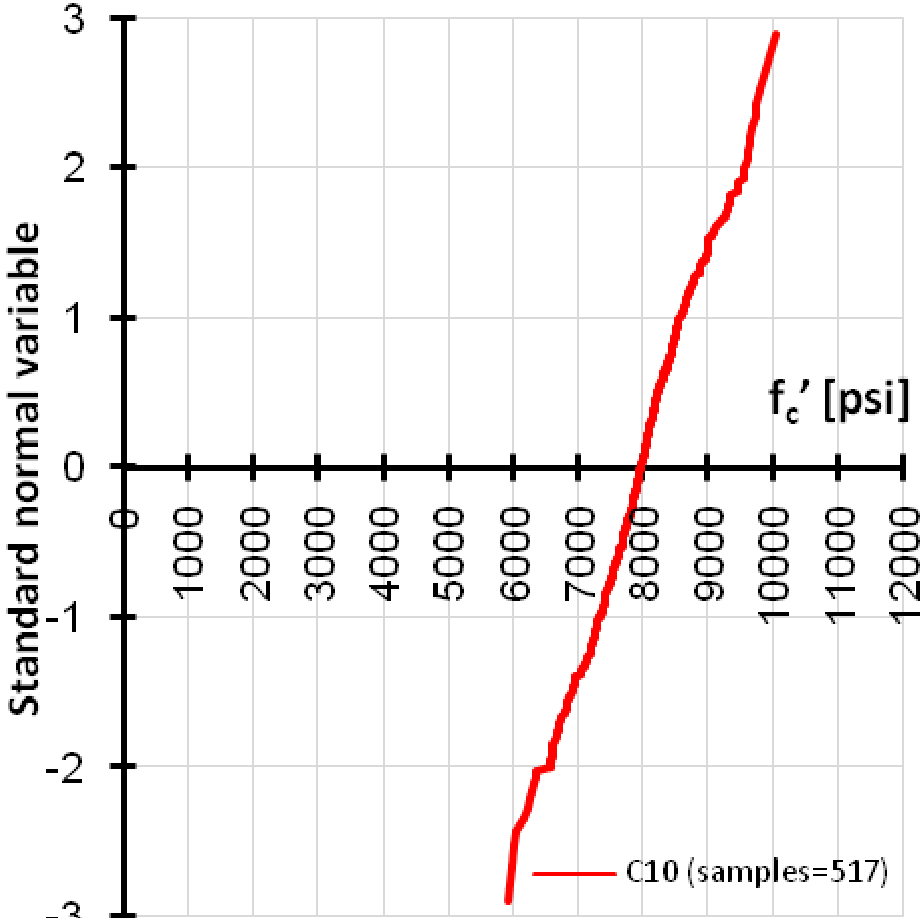
Lightweight Concrete – CDF of Strength

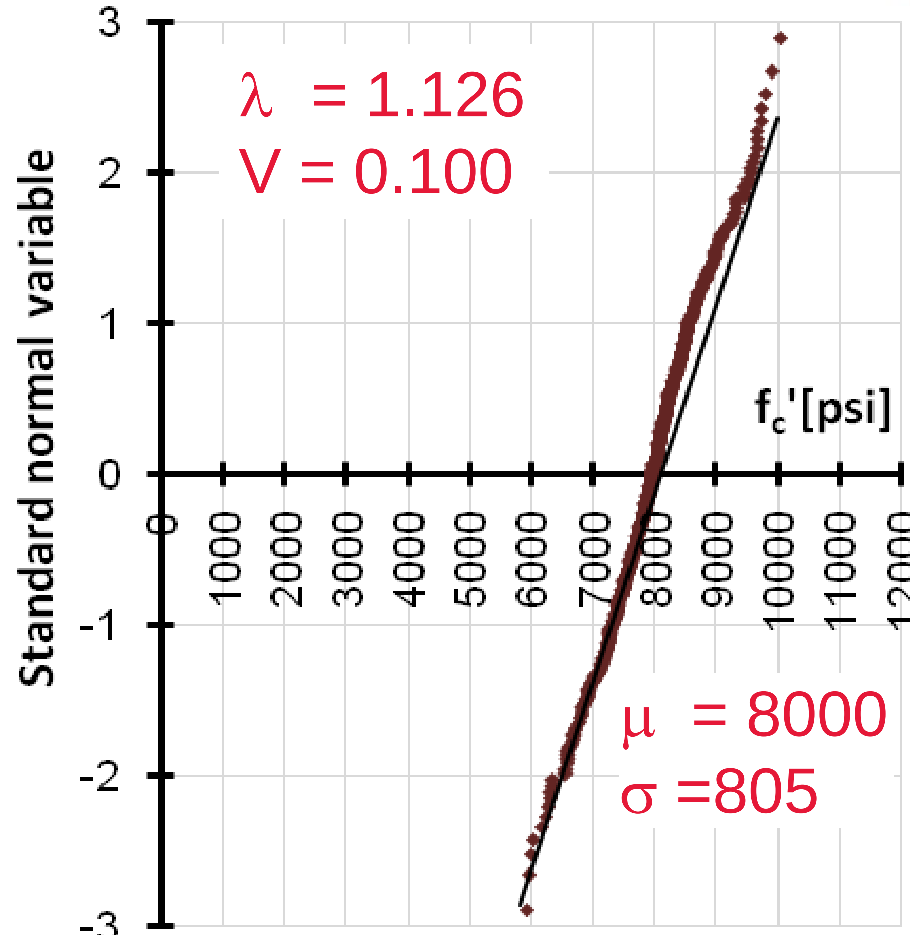




f_c'= 6800 psi , 48 MPa

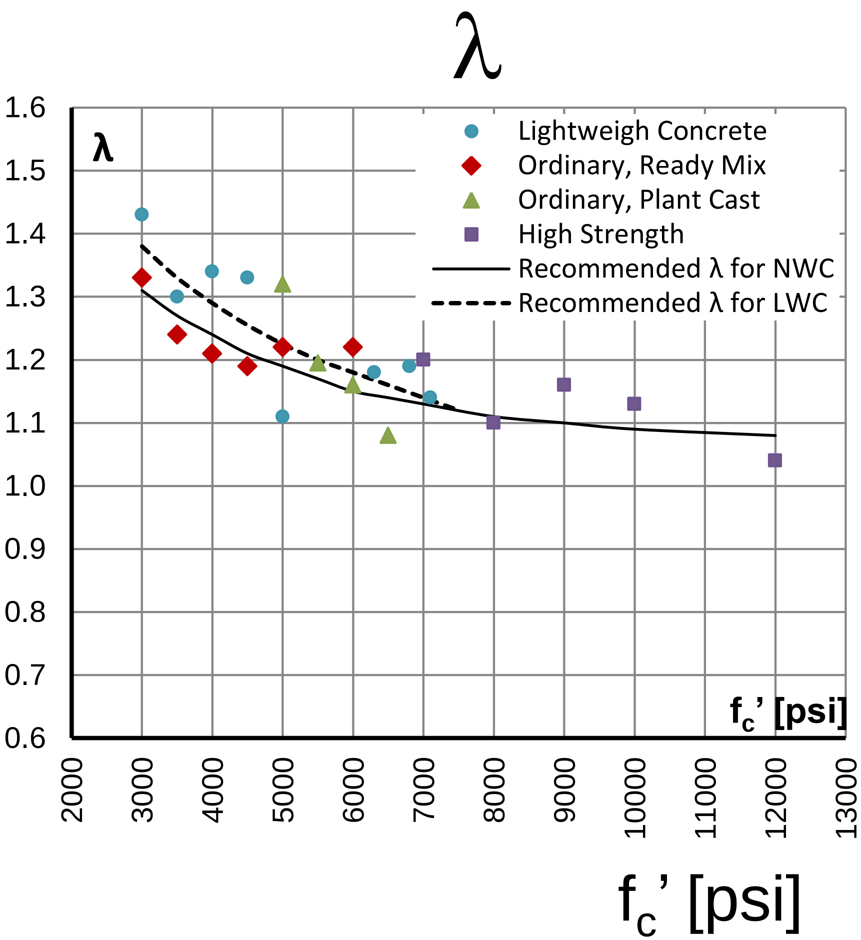
Lightweight Concrete – CDF of Strength

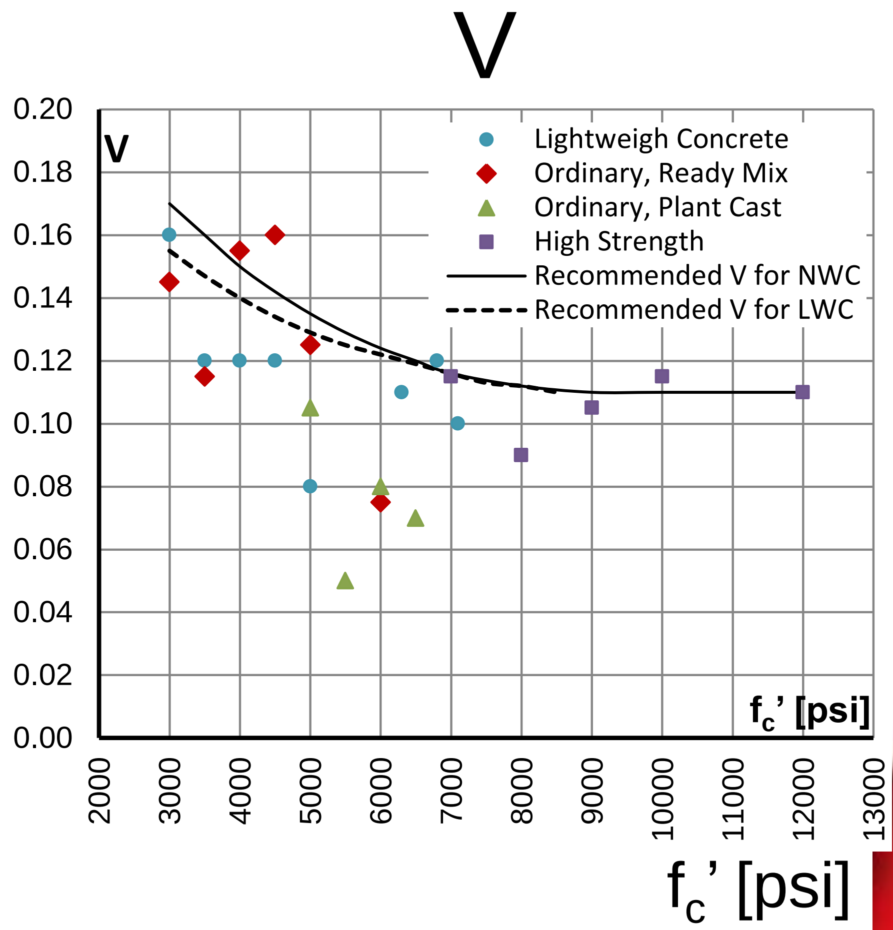




f_c'= 7100 psi, 49 MPa

Summary of the Statistical Parameters for Concrete





Bias Factor and Coefficient of Variation for Compressive Strength and Shear Strength of Concrete

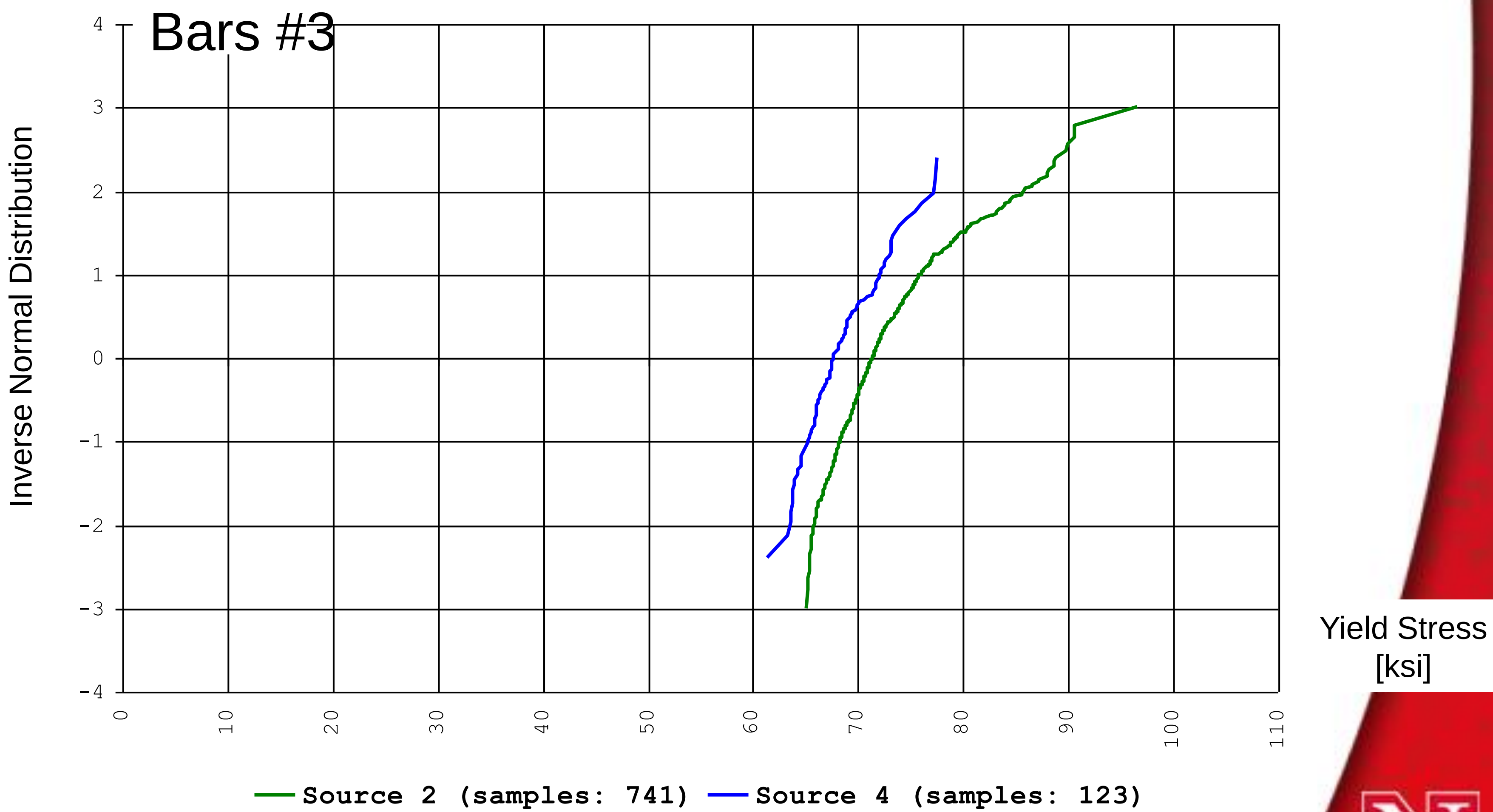
Concrete Grade f_c' (psi)	Compressive strength		Shear Strength	
	λ	V	λ	V
3000, 21 MPa	1.31	0.17	1.31	0.205
3500	1.27	0.16	1.27	0.19
4000, 28 MPa	1.24	0.15	1.24	0.18
4500	1.21	0.14	1.21	0.17
5000	1.19	0.135	1.19	0.16
5500	1.17	0.13	1.17	0.155
6000, 42 MPa	1.15	0.125	1.15	0.15
6500	1.14	0.12	1.14	0.145
7000	1.13	0.115	1.13	0.14
8000	1.11	0.11	1.11	0.135
9000	1.10	0.11	1.10	0.135
10,000	1.09	0.11	1.09	0.135
12,000, 84 MPa	1.08	0.11	1.08	0.135

Reinforcing Steel Bars, Grade 60 (420 MPa) – Number of Samples

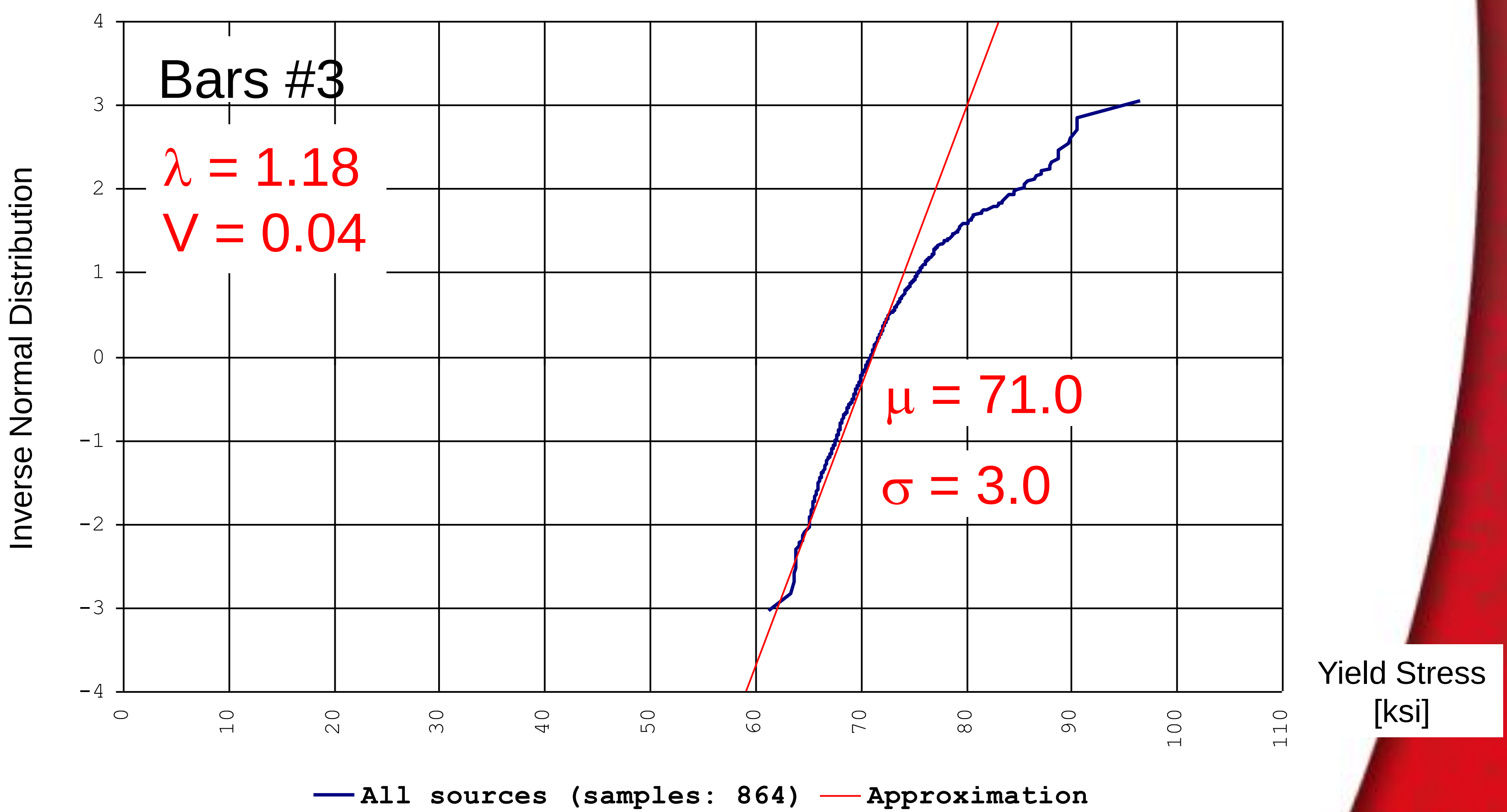
Bar Size:

Source:	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	Total:
1		60	60	60	60	60	60	60	60		
2	741	2369	3333	1141	1318	1146	1290	825	1019		
3		60	60	60	60	60	60	60	60	12	
4	123	106	179	104	79	90	73	70	87		
5		90	90	90	90	90	90	74	90		
Total:	864	2685	3722	1455	1607	1446	1573	1089	1316	12	15769

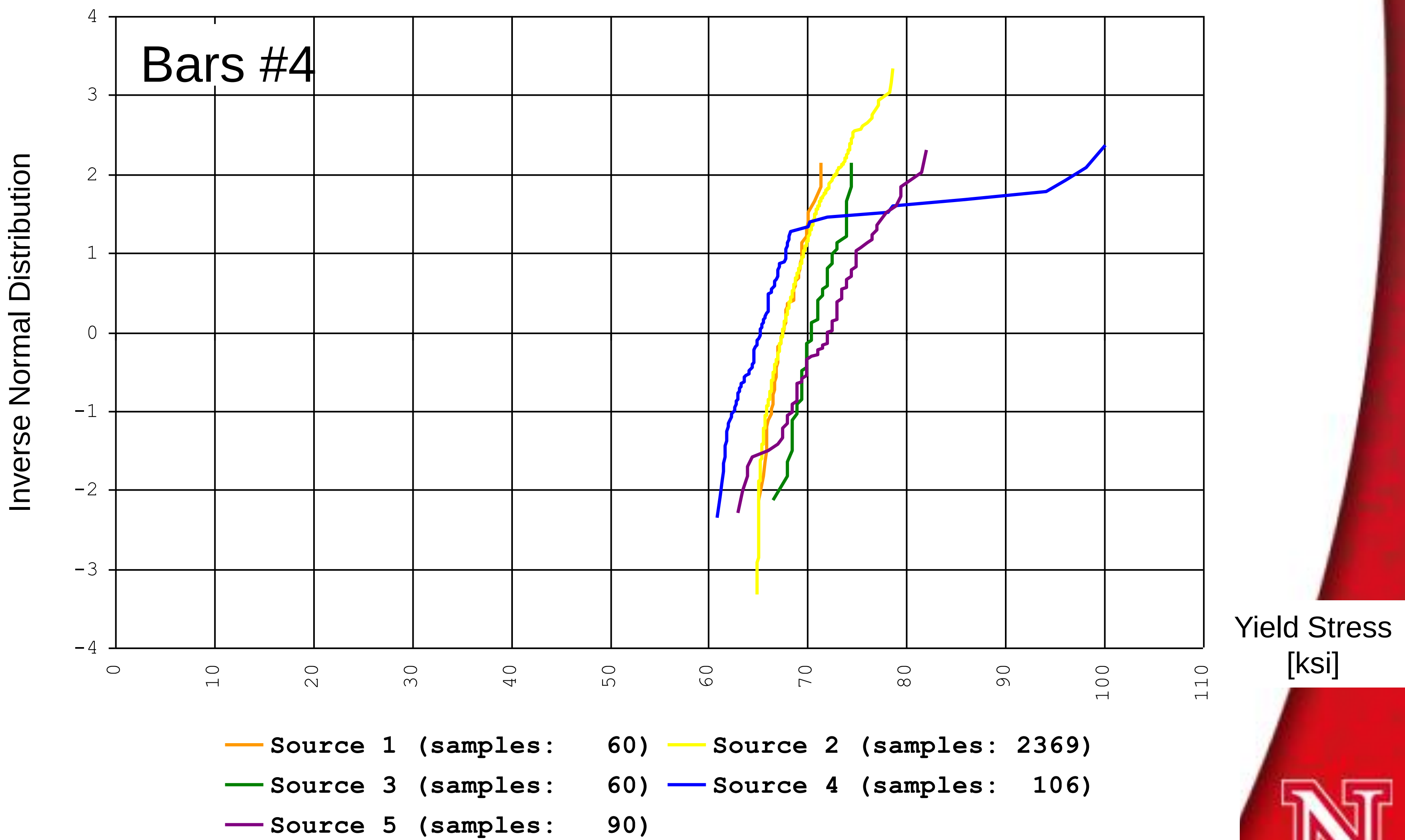
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



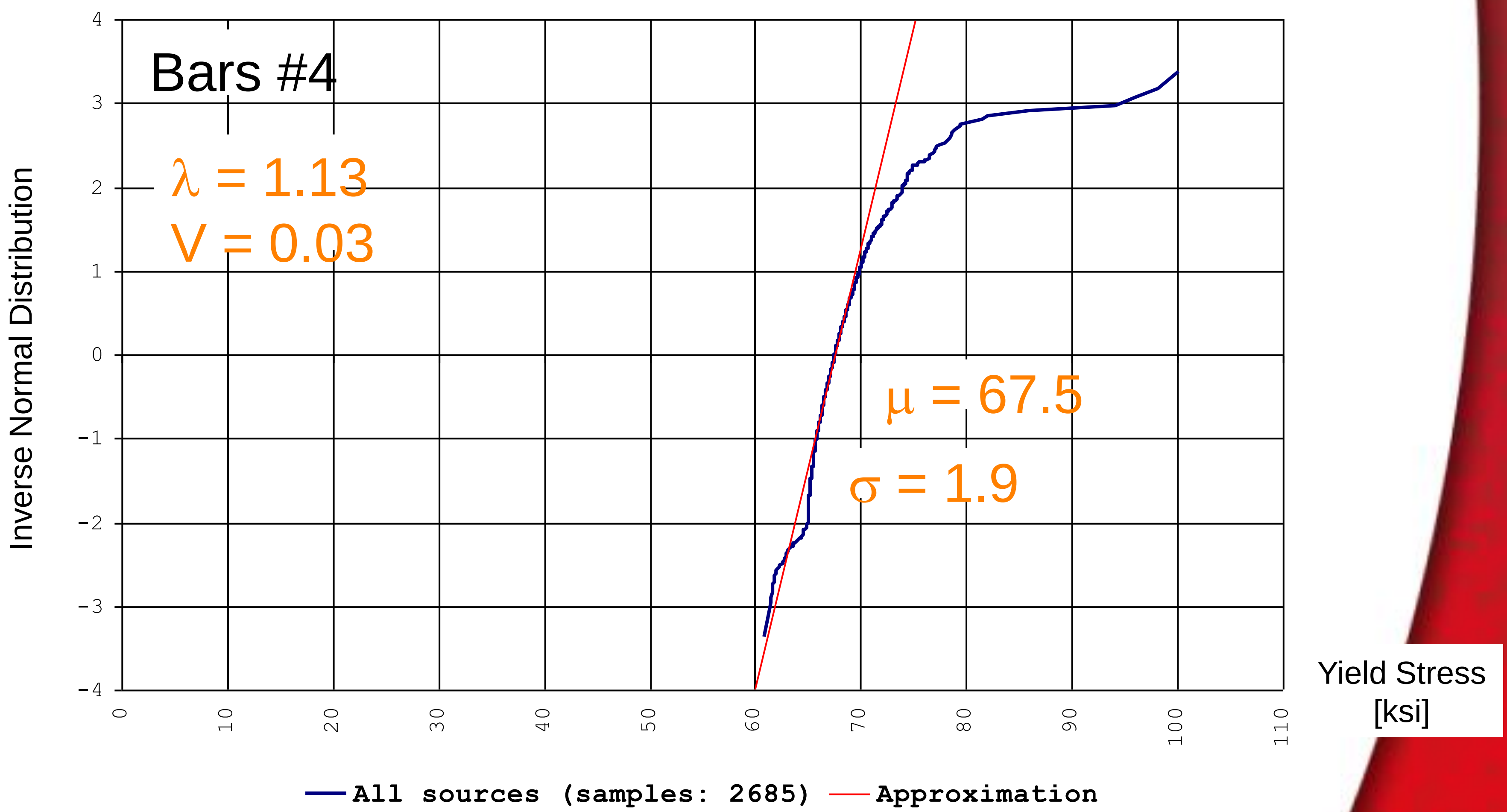
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



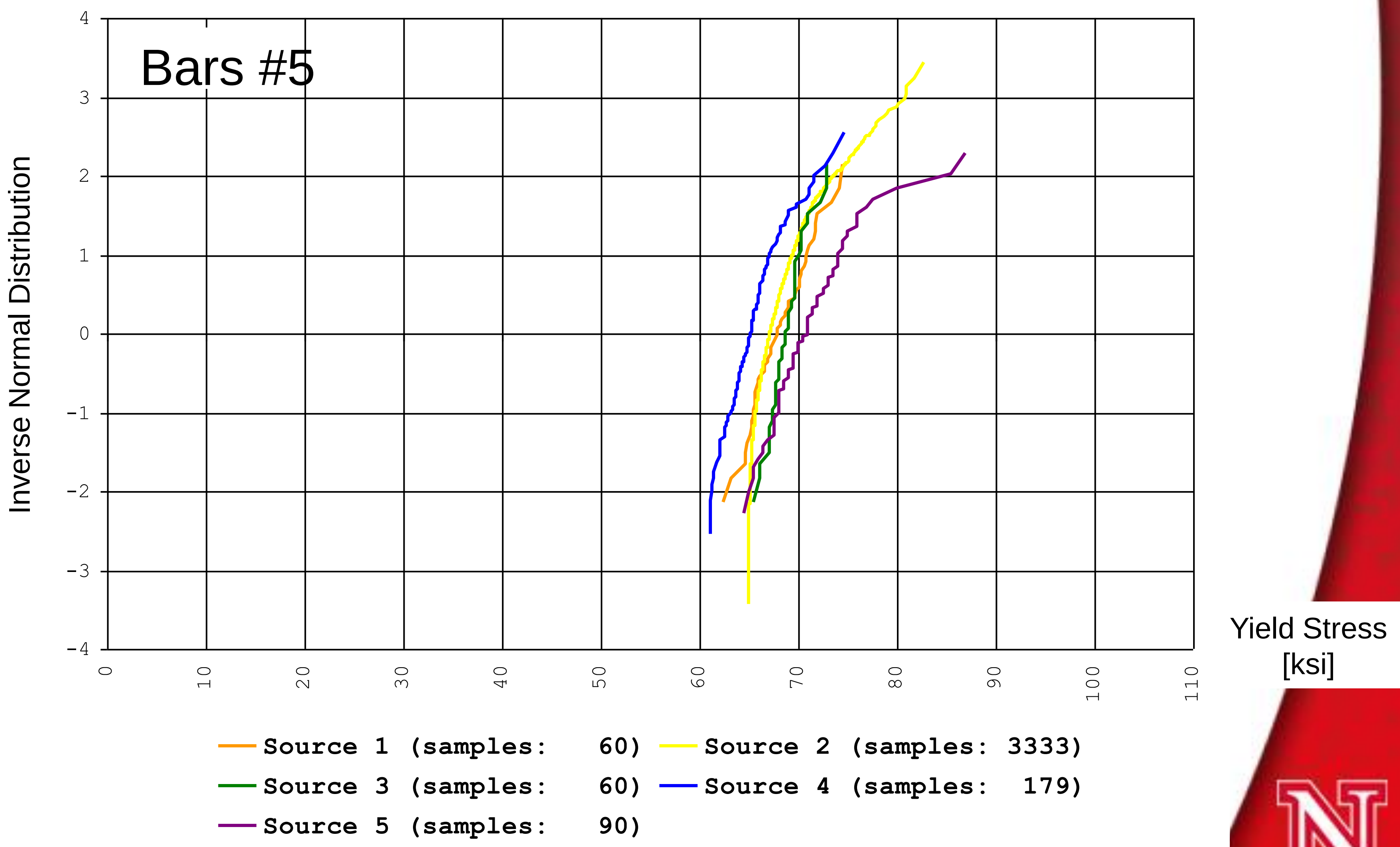
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



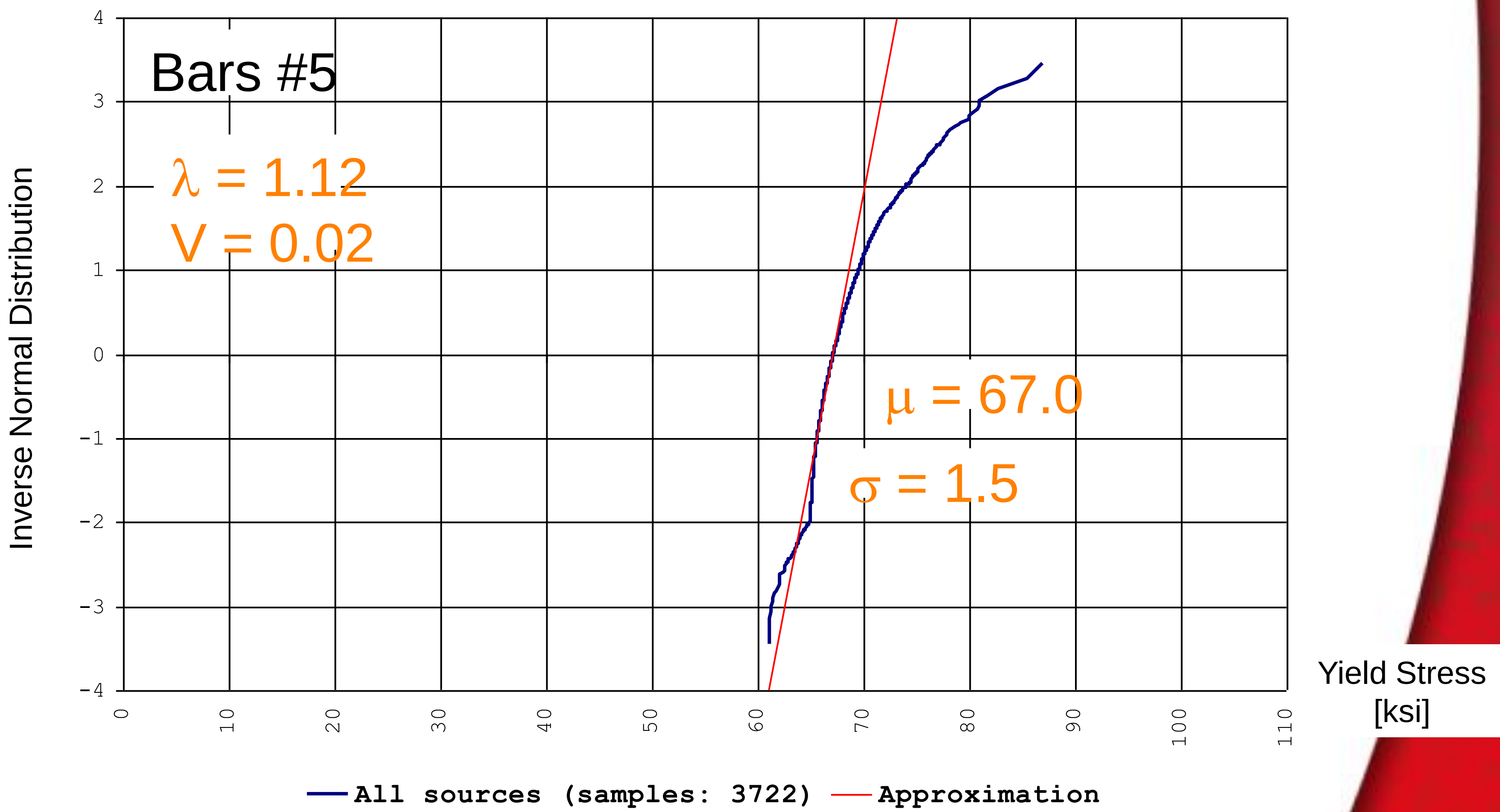
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



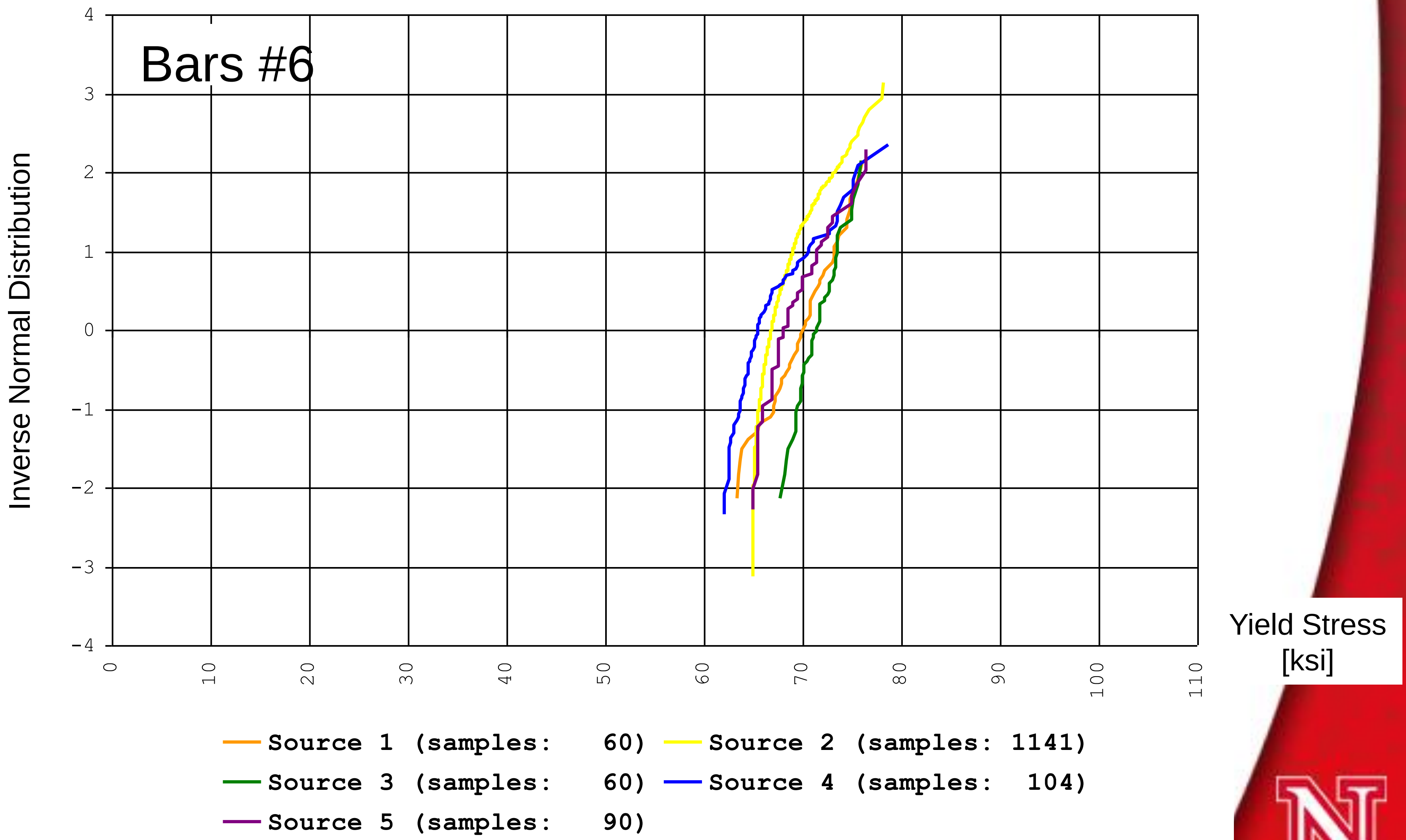
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



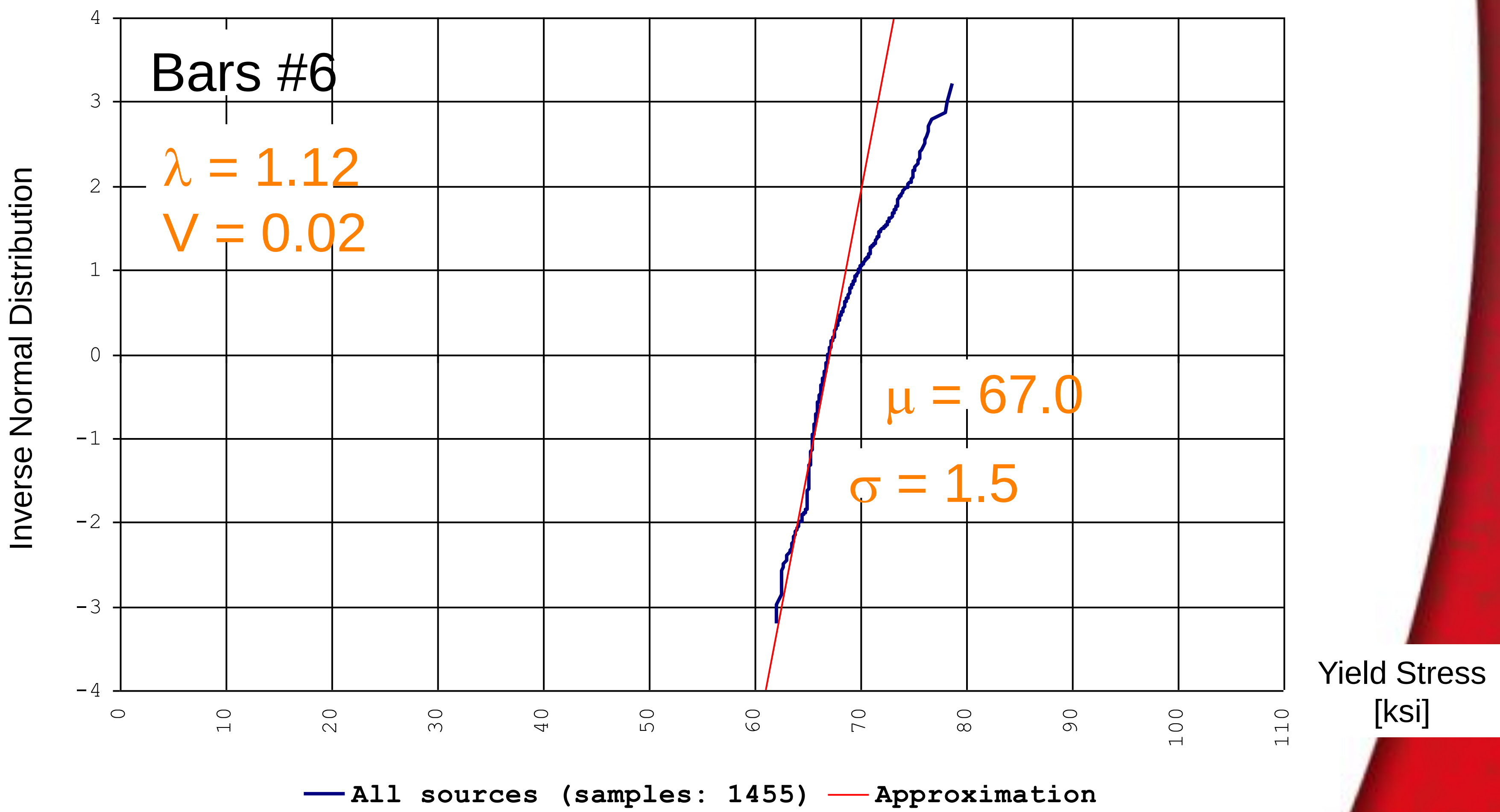
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



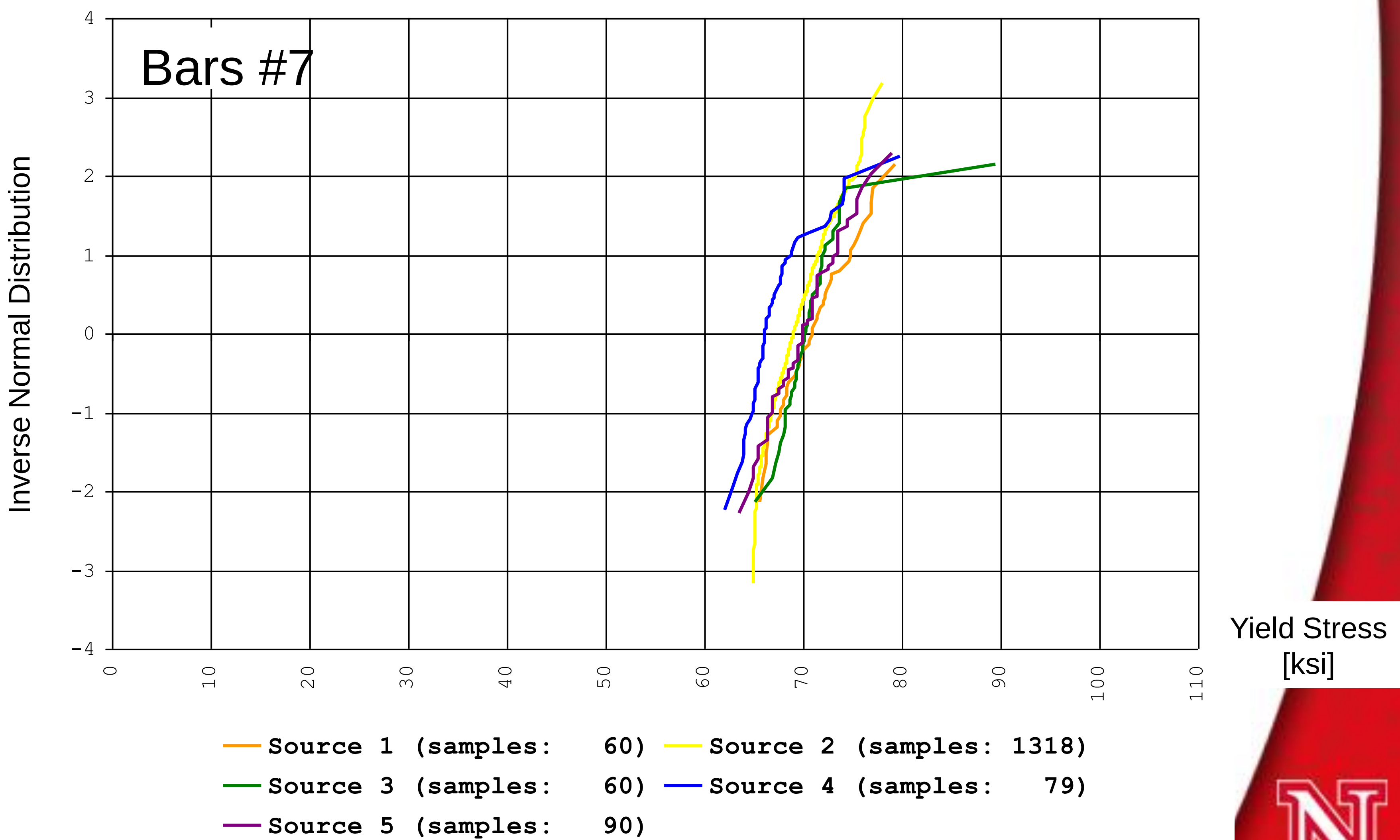
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



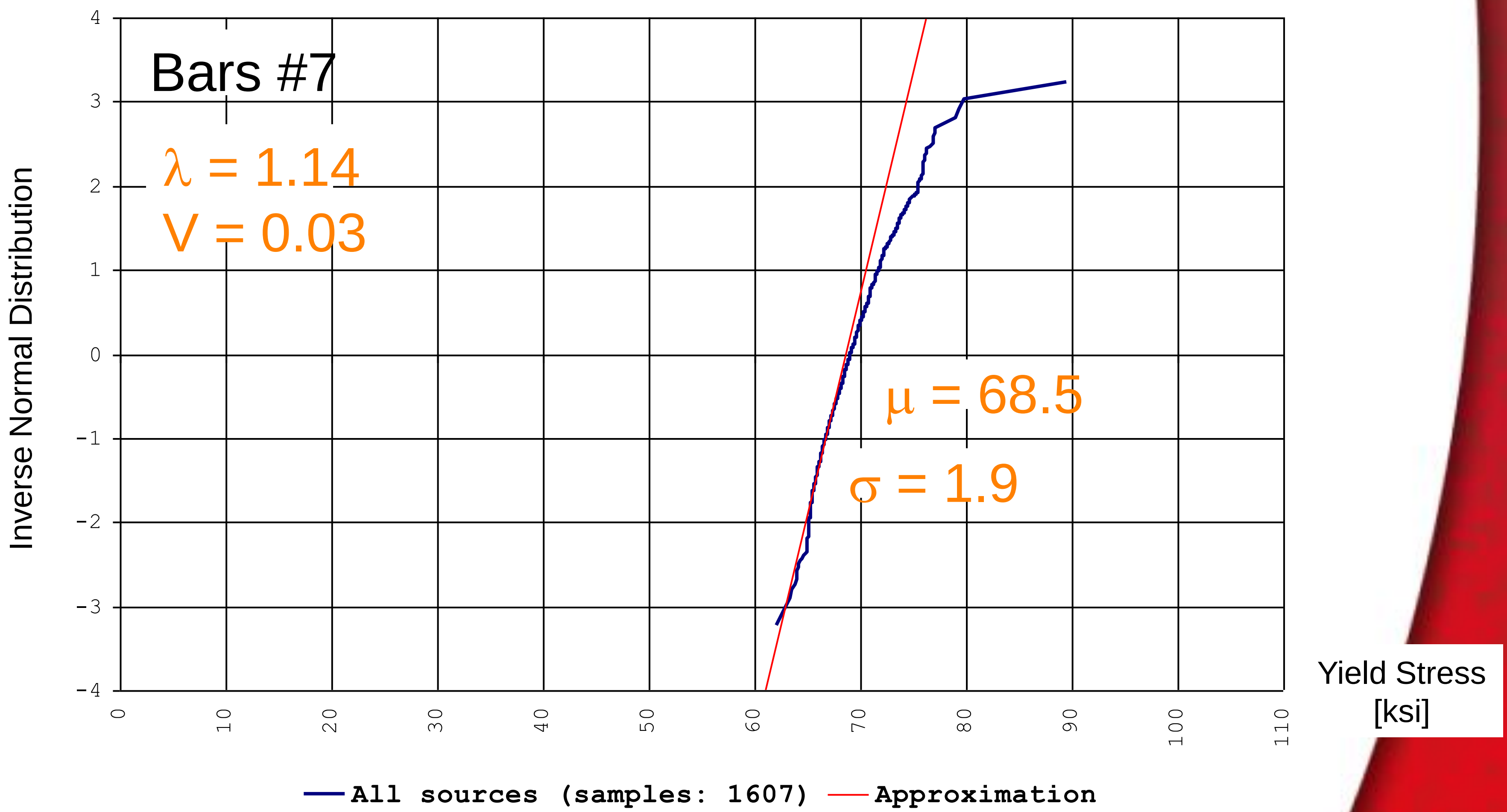
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



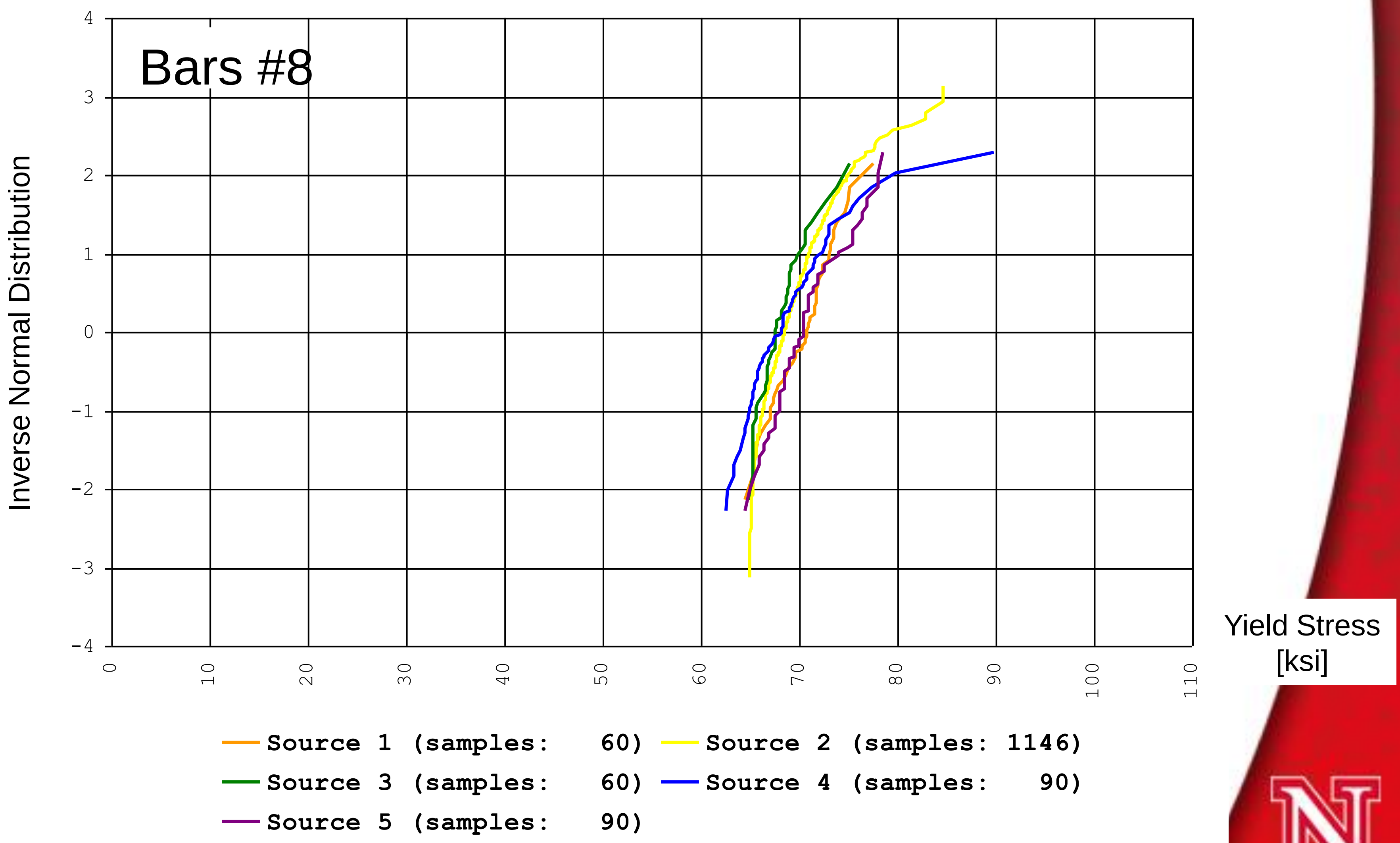
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



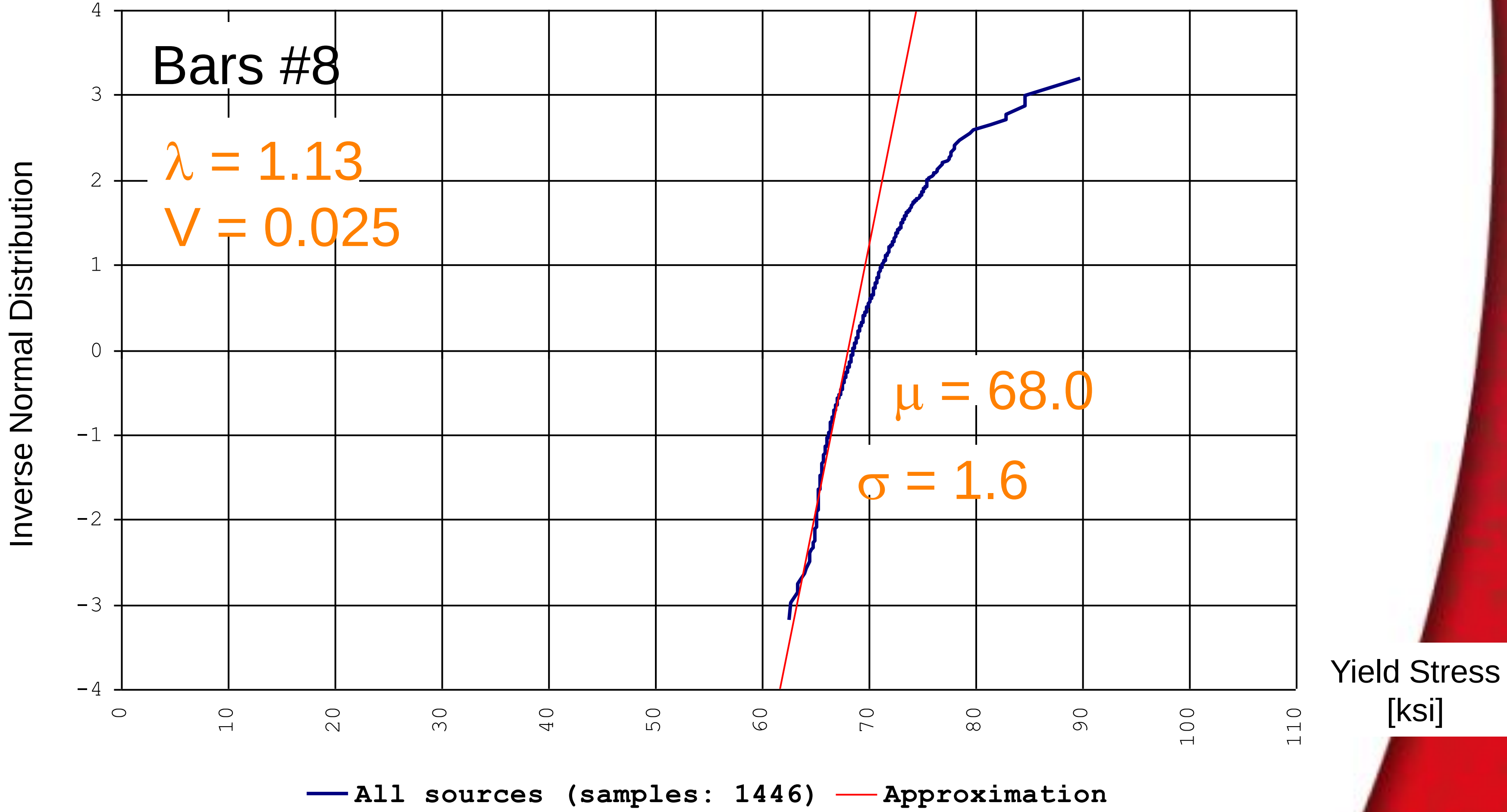
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



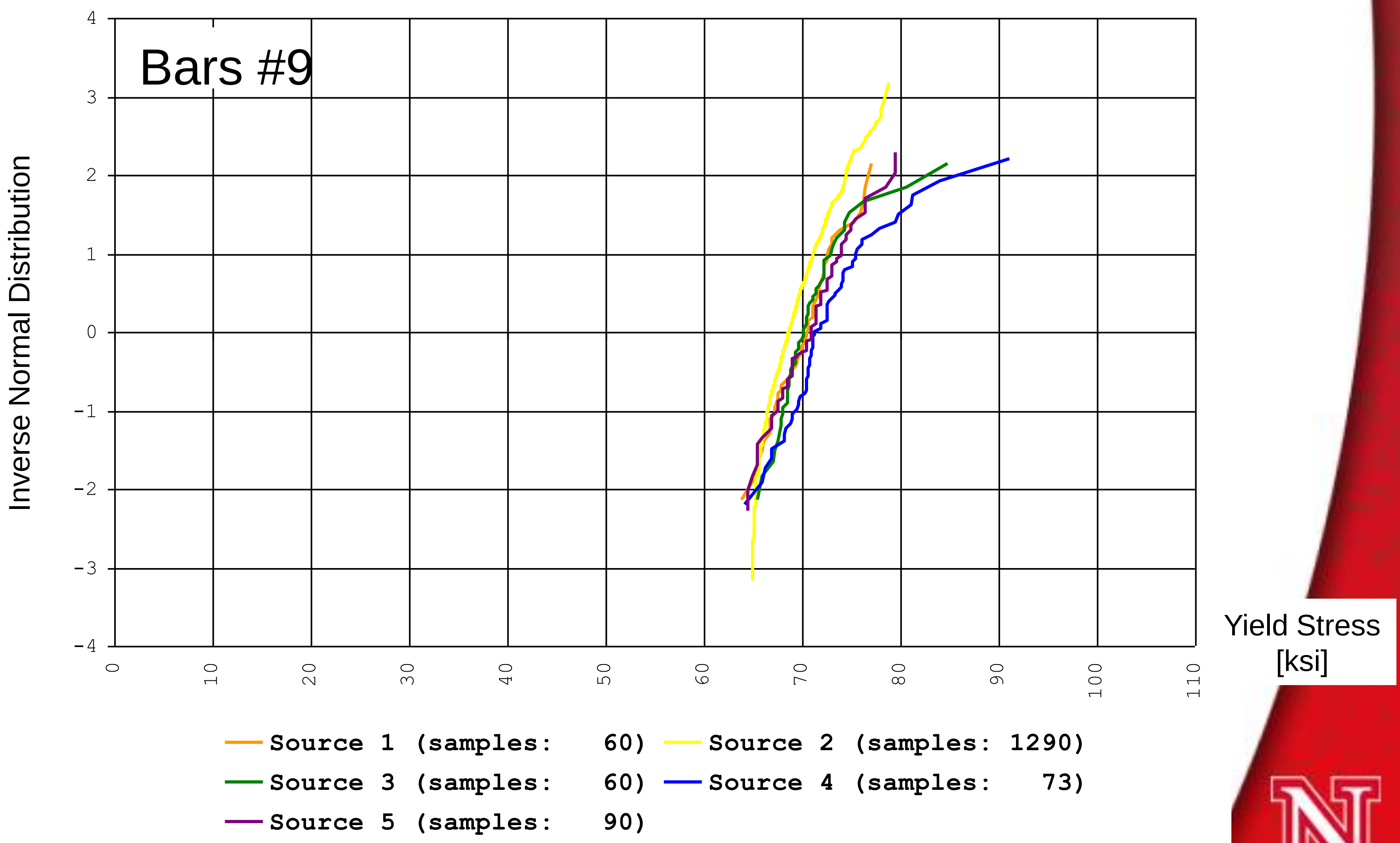
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



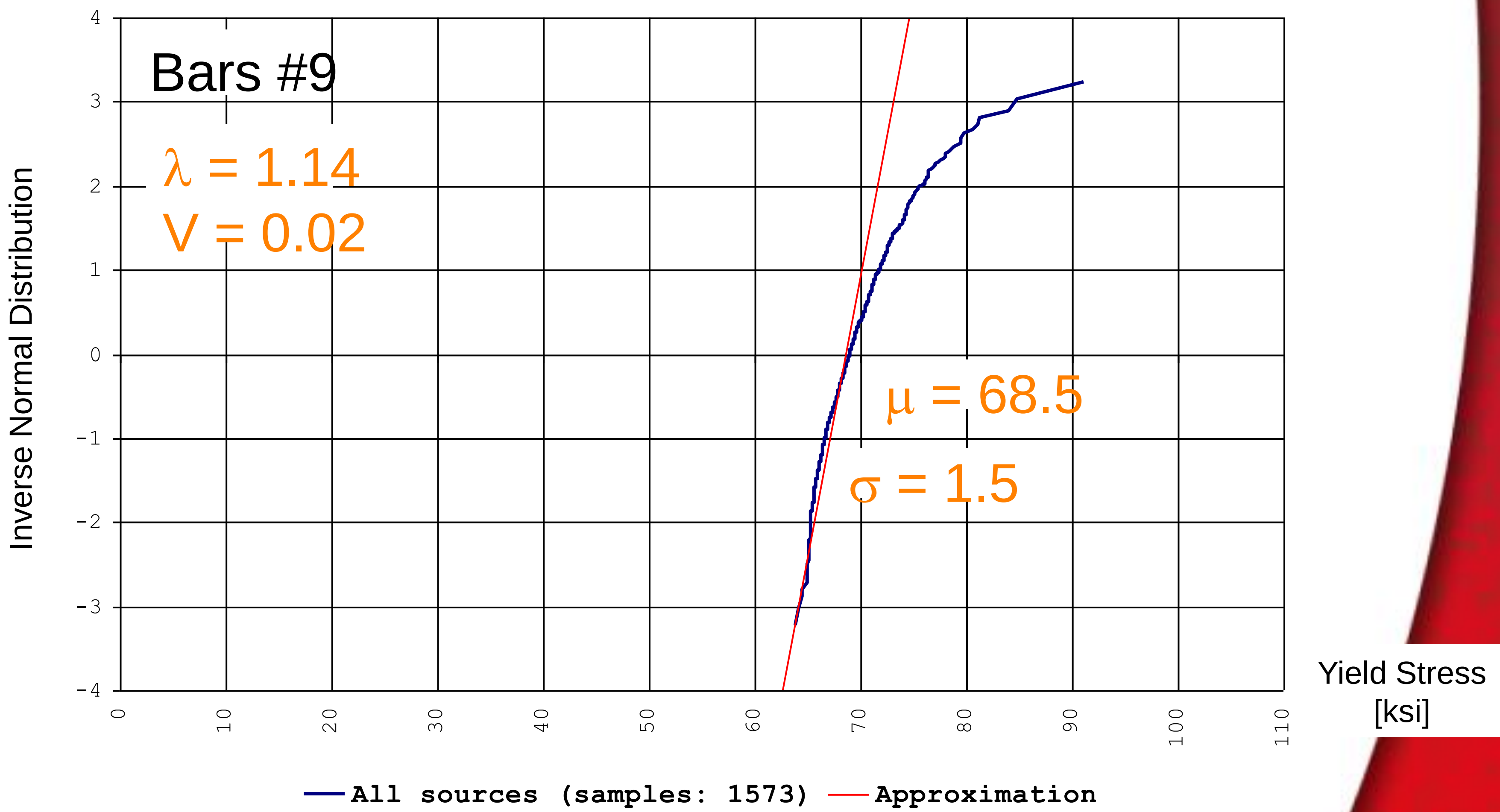
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



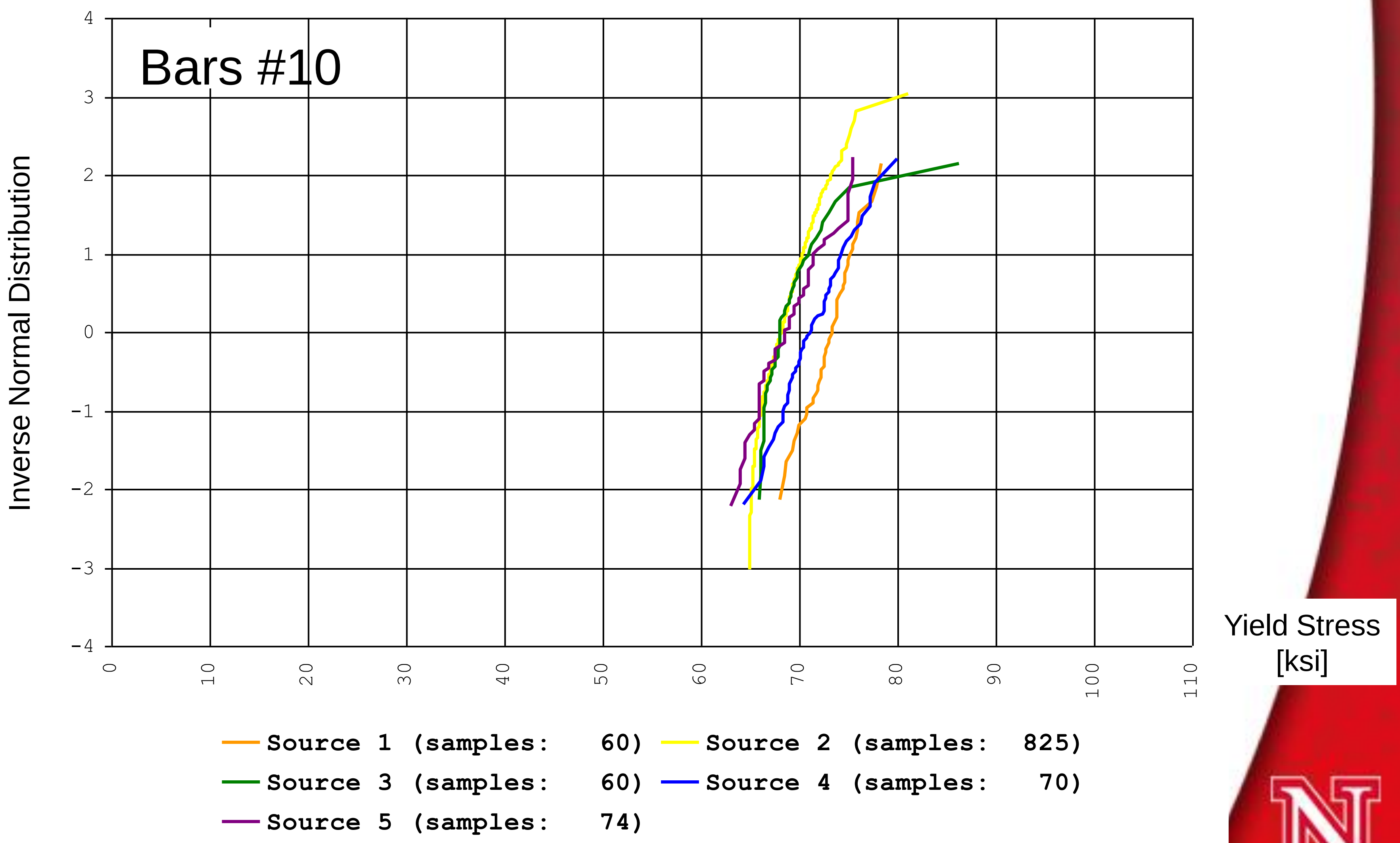
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



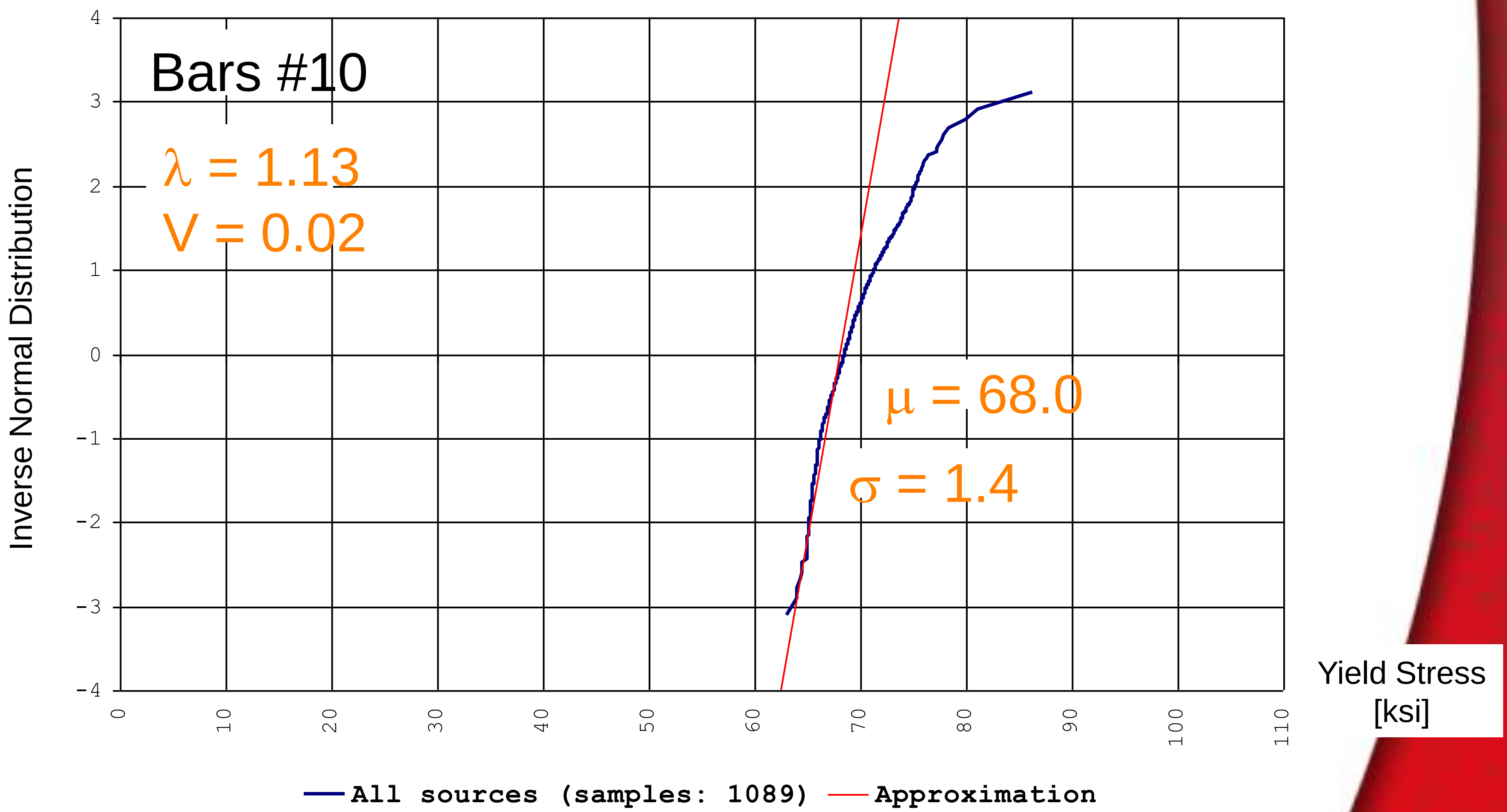
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



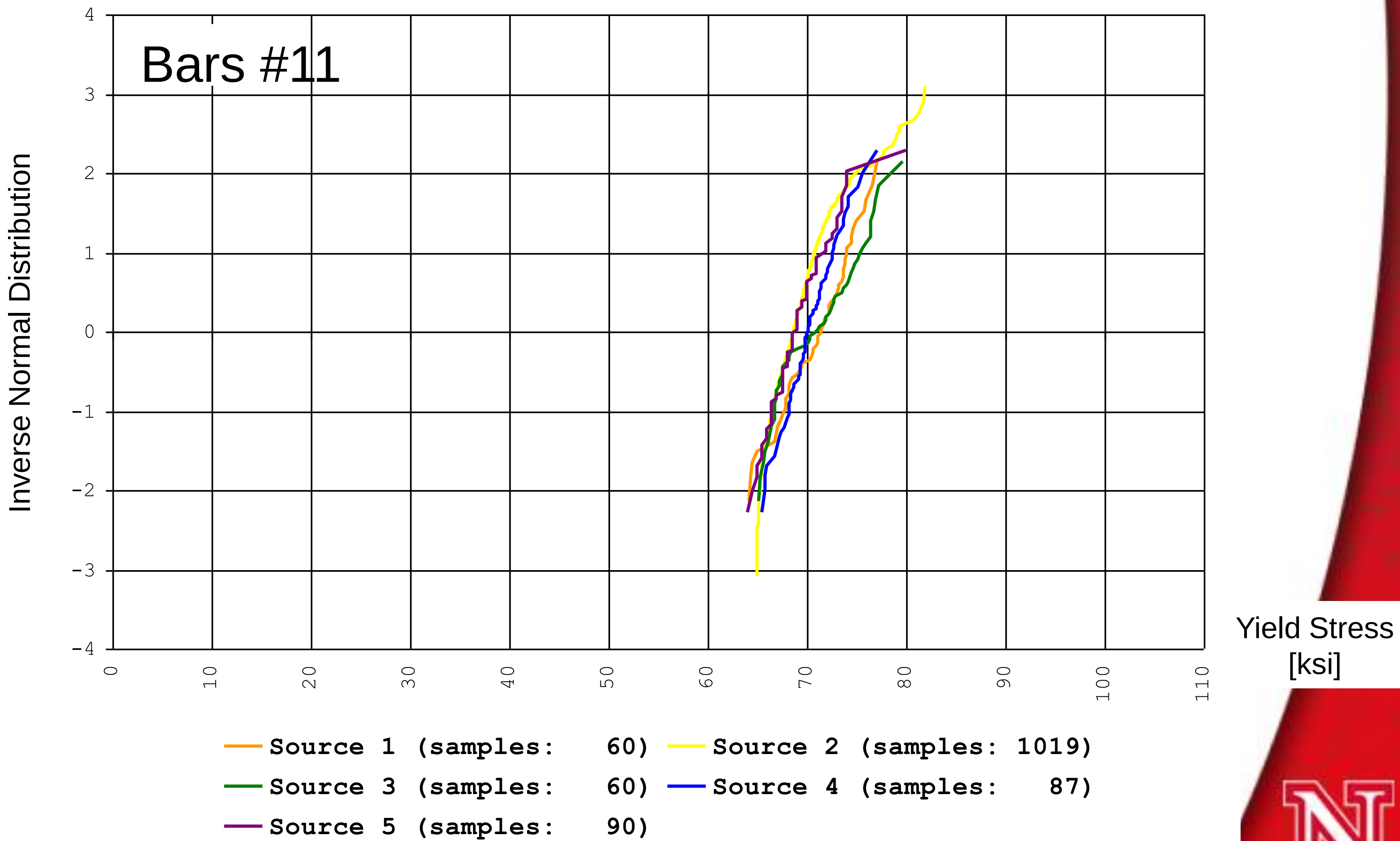
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



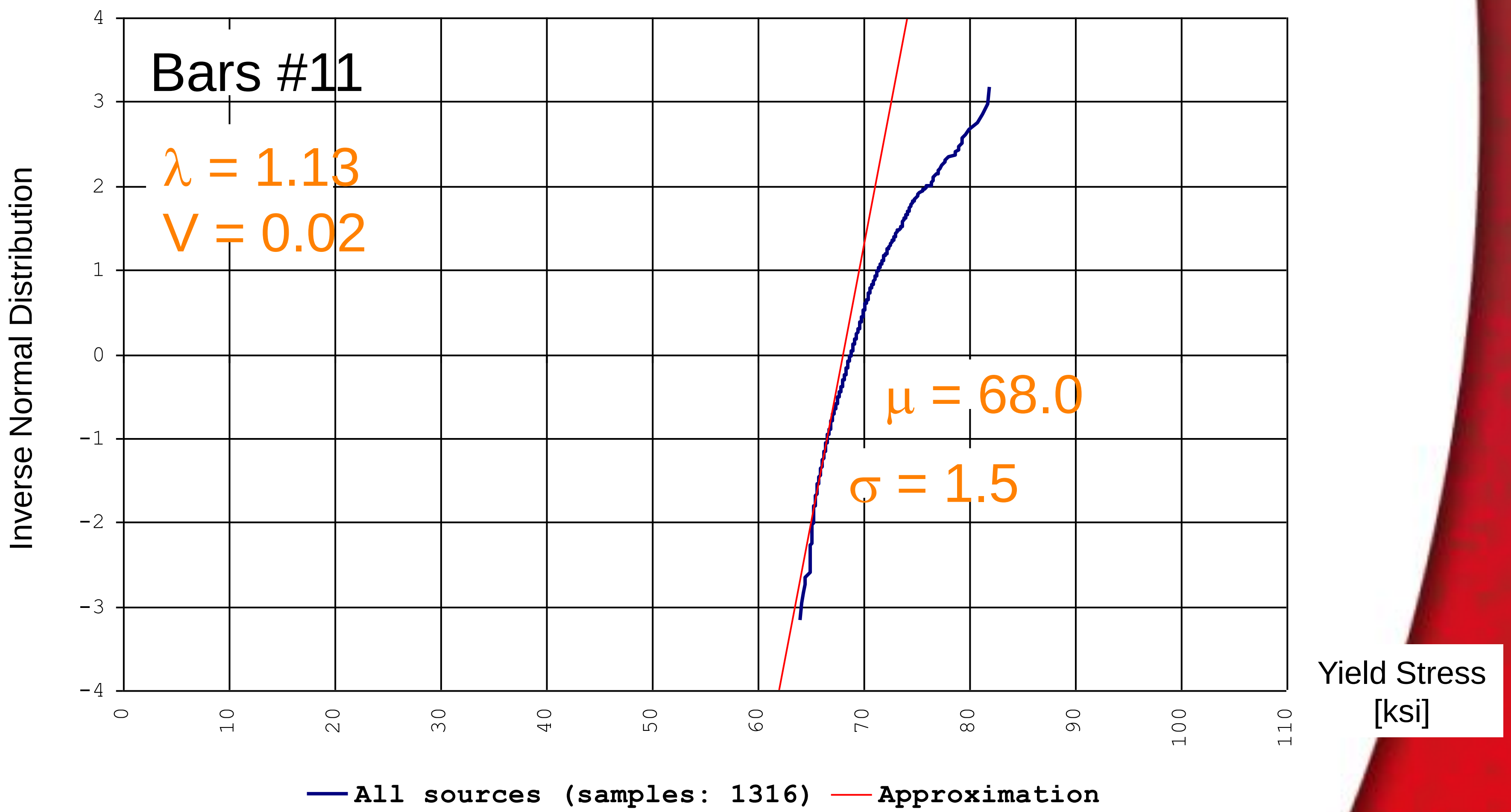
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



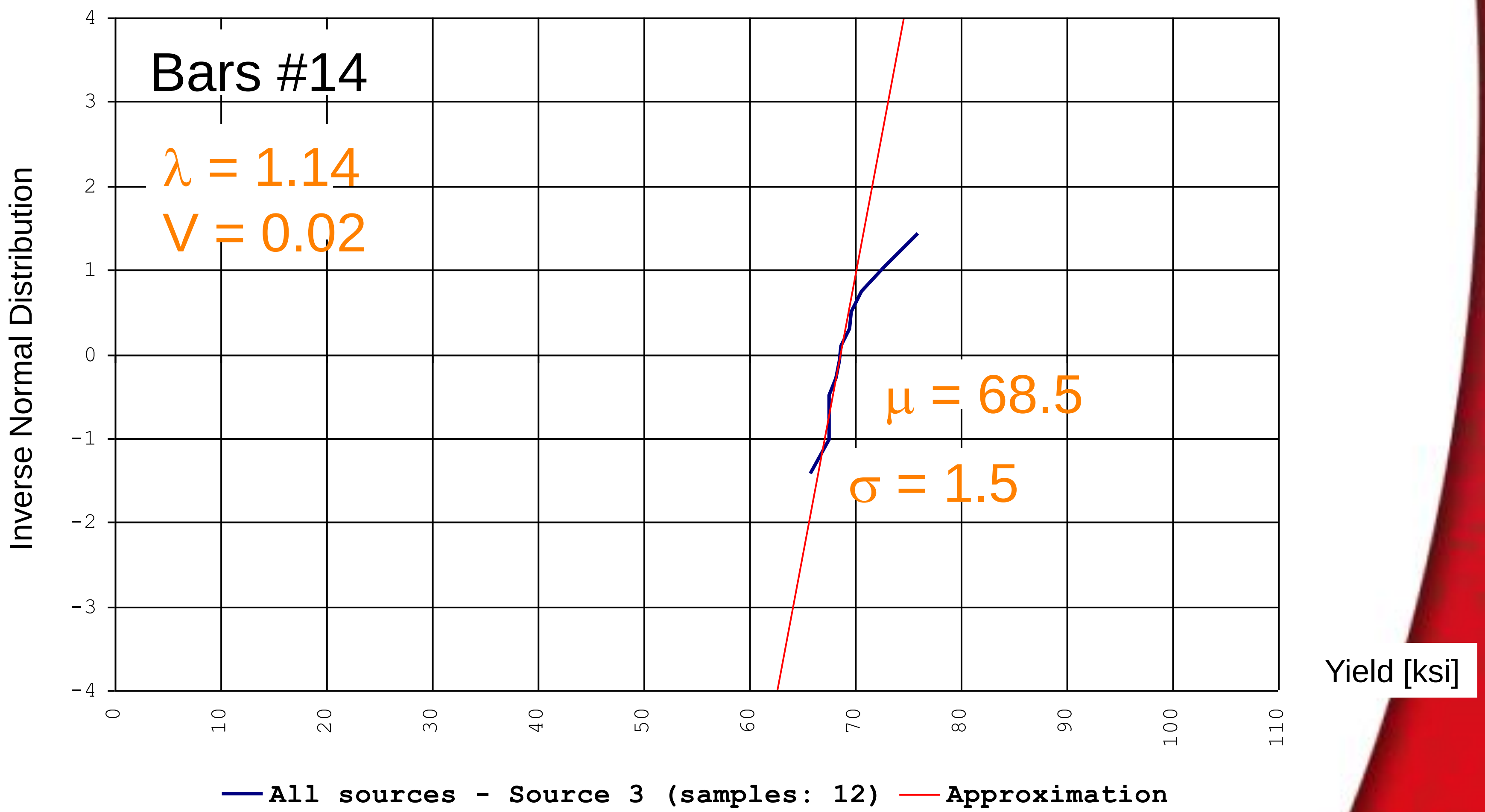
Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress

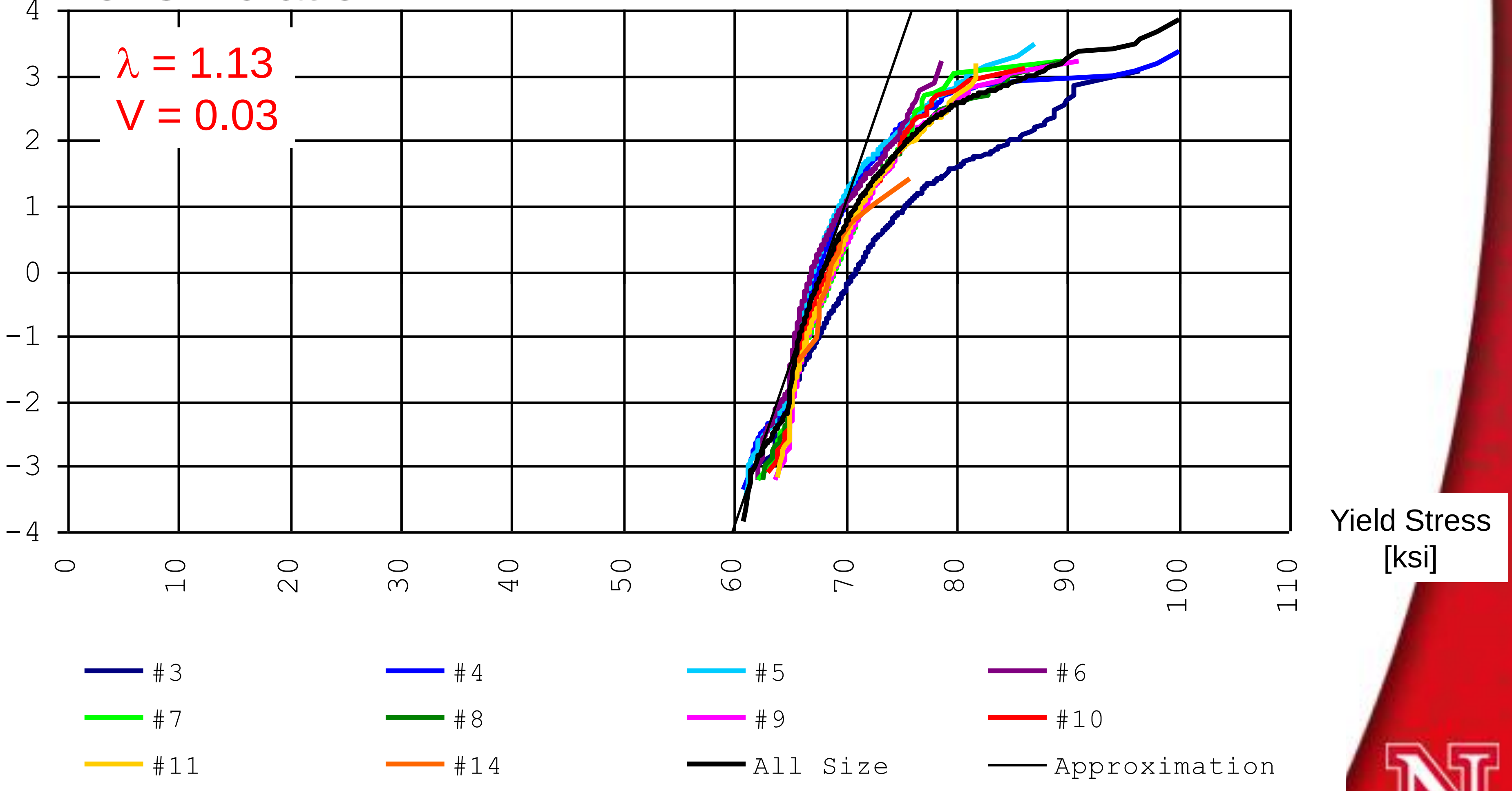


Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress



Reinforcing Steel Bars, Grade 60 – CDF of Yield Stress

for simulation:



Reinforcing Steel Bars, Grade 60 (420 MPa) – Statistical Parameters

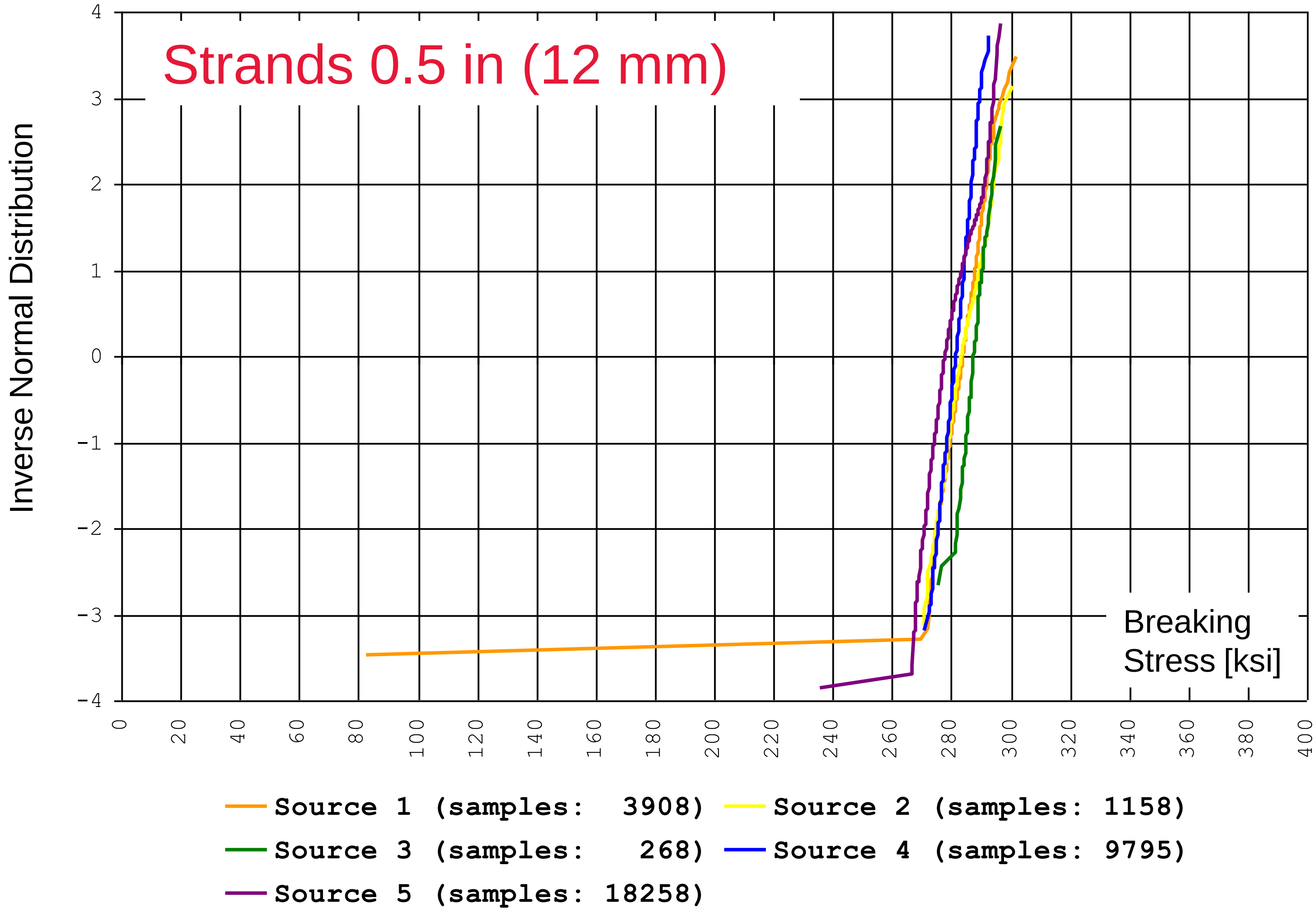
Bar Size	λ	V
# 3	1.18	0.04
# 4	1.13	0.03
# 5	1.12	0.02
# 6	1.12	0.02
# 7	1.14	0.03
# 8	1.13	0.025
# 9	1.14	0.02
#10	1.13	0.02
#11	1.13	0.02
#14	1.14	0.02

Prestressing Strands Grade 270 (1800 MPa) – Number of Samples

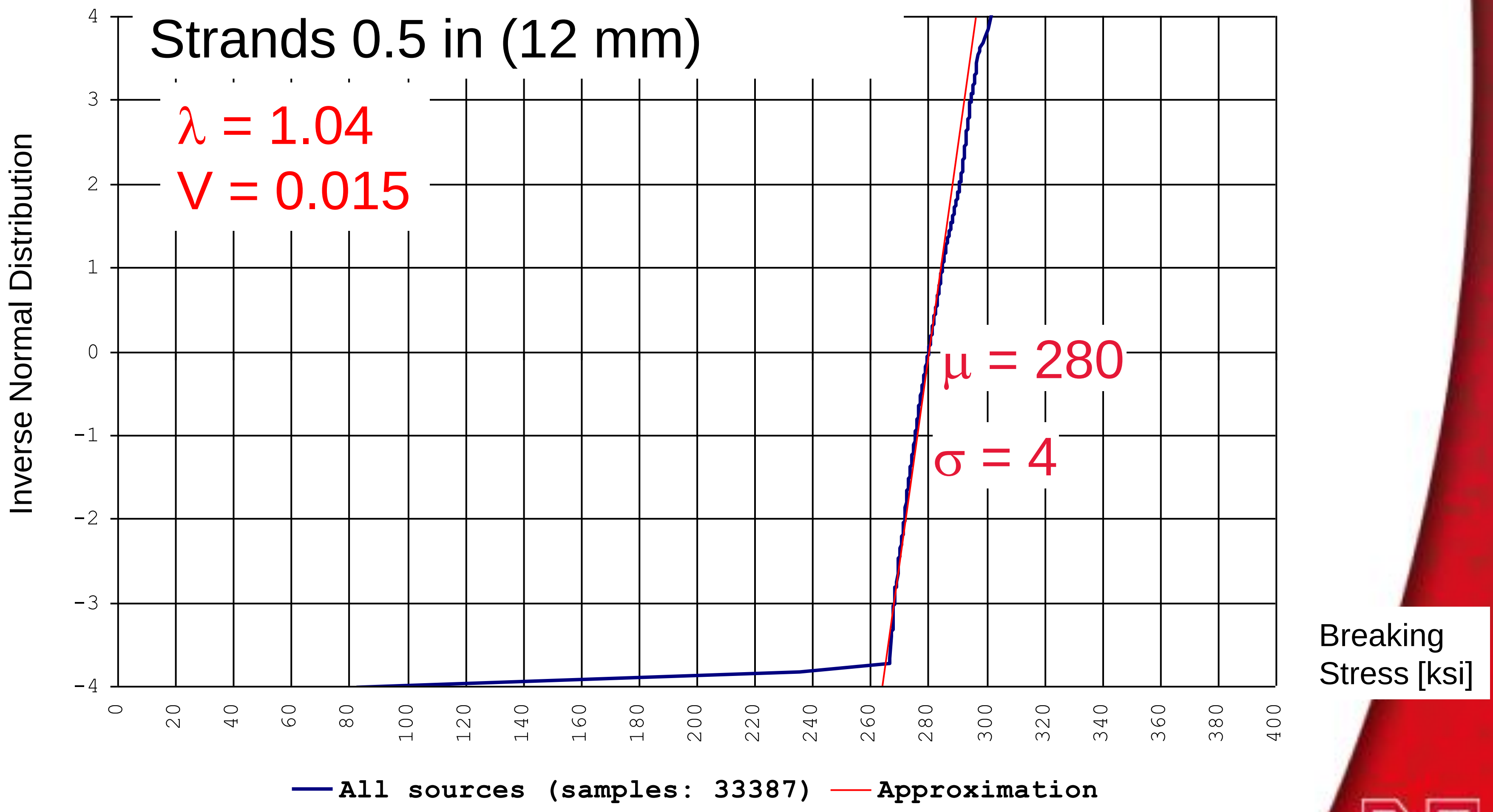
Strand diameter / Source	Number of samples	
	0.5in	0.6in
Source 1	3,908	700
Source 2	1,158	785
Source 3	268	212
Source 4	9,795	3,442
Source 5	18,258	8,895
Total	**33,387**	**14,034**

Total Number of Samples 47,421

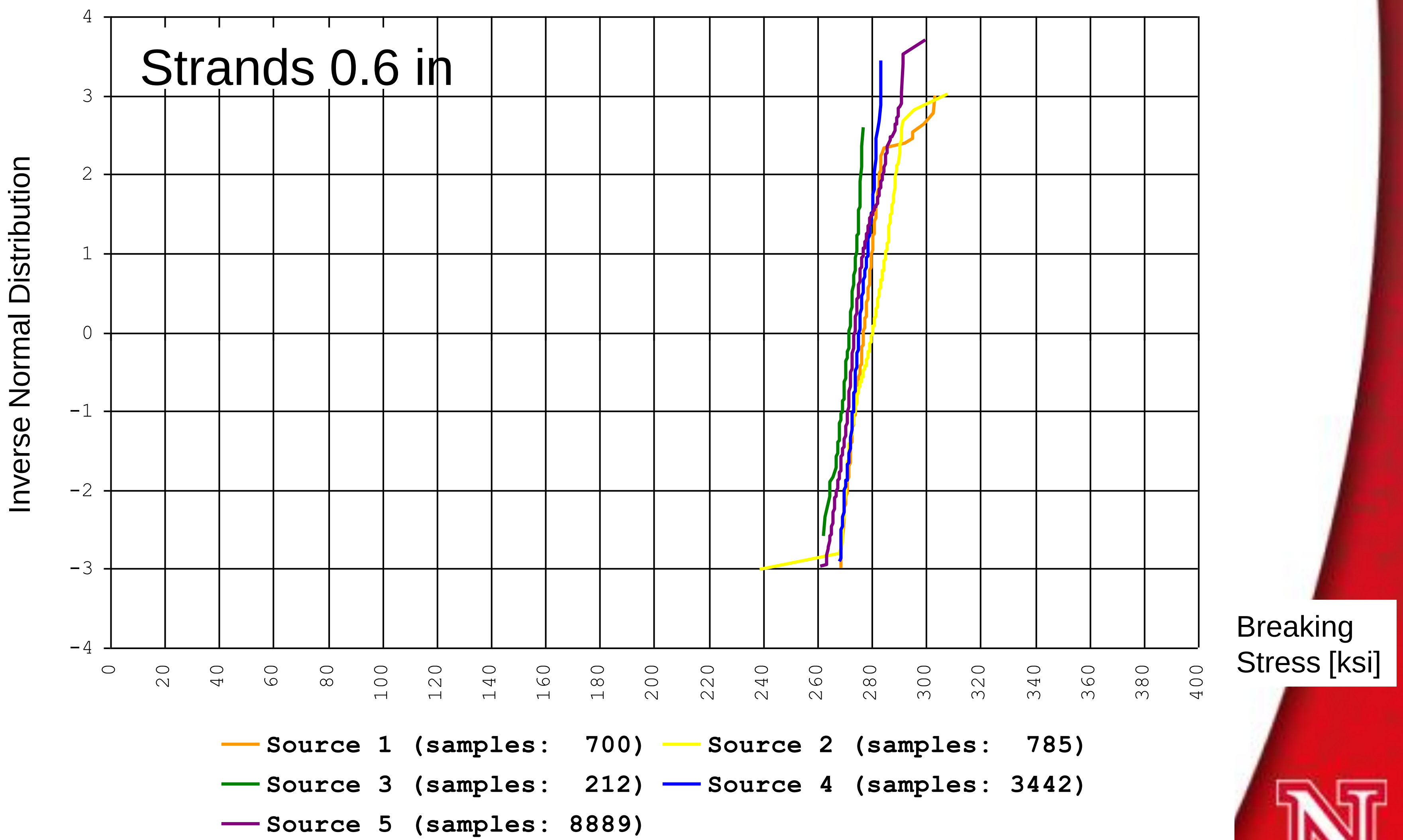
Prestressing Steel (7-wire strands), Grade 270
CDF of Breaking Stress



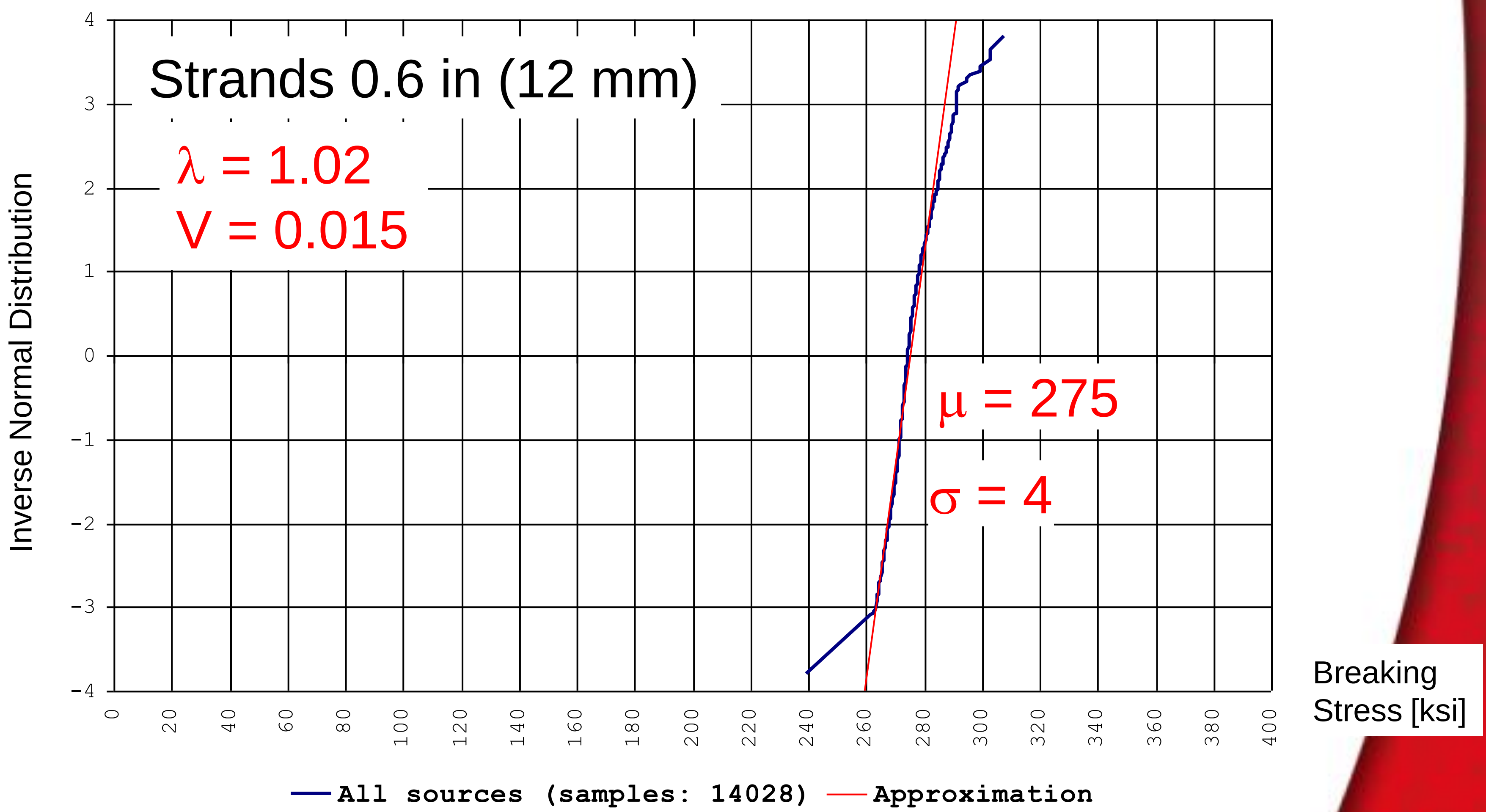
Prestressing Steel (7-wire strands), Grade 270
CDF of Breaking Stress



Prestressing Steel (7-wire strands), Grade 270
CDF of Breaking Stress



Prestressing Steel (7-wire strands), Grade 270
CDF of Breaking Stress



Prestressing Steel – Statistical Parameters

Grade	Size	Number of samples	Bias Factor	V
250 ksi (1750 MPa)	1/4 (6.25 mm) 3/8 (9.5 mm) 7/16(11 mm) 1/2 (12.5 mm)	22 83 114 66	1.07 1.11 1.11 1.12	0.01 0.025 0.01 0.02
270 ksi (1900 MPa)	3/8 (9.5 mm) 7/16 (11 mm) 1/2 (12.5 mm) 0.6 (15 mm)	54 16 33570 14028	1.04 1.07 1.04 1.02	0.02 0.02 0.015 0.015

Structural elements and limit states

- Reinforced concrete beams - flexure
- Reinforced concrete beams - shear (w/o stirrups)
- Reinforced concrete beams - shear (with stirrups)
- Axially loaded columns, tied
- Axially loaded columns, spiral
- One way slabs - flexure
- One way slabs - shear
- Two way slabs – shear
- Bearing strength

Bending Moment Resistance

$$R = \left(A_s \times f_y\right)\left(d - \frac{a}{2}\right)$$

$$a = \frac{A_s . f_y}{0.85 f'_c . b}$$

for beams ρ = 0.6 and 1.6%,
for slabs ρ = 0.30%.

Shear Resistance of Flexural Members

$$R = V_n = V_c + V_s$$

$$V_C = 2\sqrt{f'_c}\, b_w . d$$

$$V_s = \frac{A_v . f_y . d}{s}$$

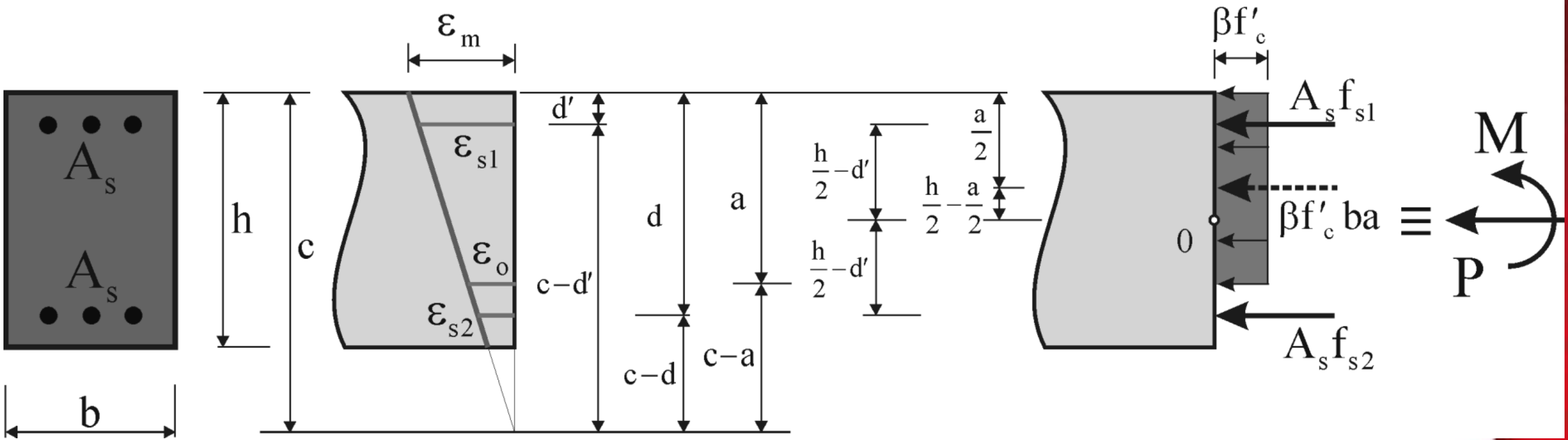
Shear Resistance of Slabs in Two-Way Shear

$$R = \min\left\{\left(1+\frac{2}{\beta_c}\right)\cdot 2\sqrt{f_c^{'}}b_0 d\,,\quad \left(\frac{\alpha_s d}{2b_0}+1\right)\cdot 2\sqrt{f_c^{'}}b_0 d\,,\quad 4\cdot\sqrt{f_c^{'}}b_0 d\right\}$$

$$\left(\sqrt{f_c^{'}}\right)_{simulations} = 0.95\left(\sqrt{f_c^{'}}\right)_{\text{nominal}}$$

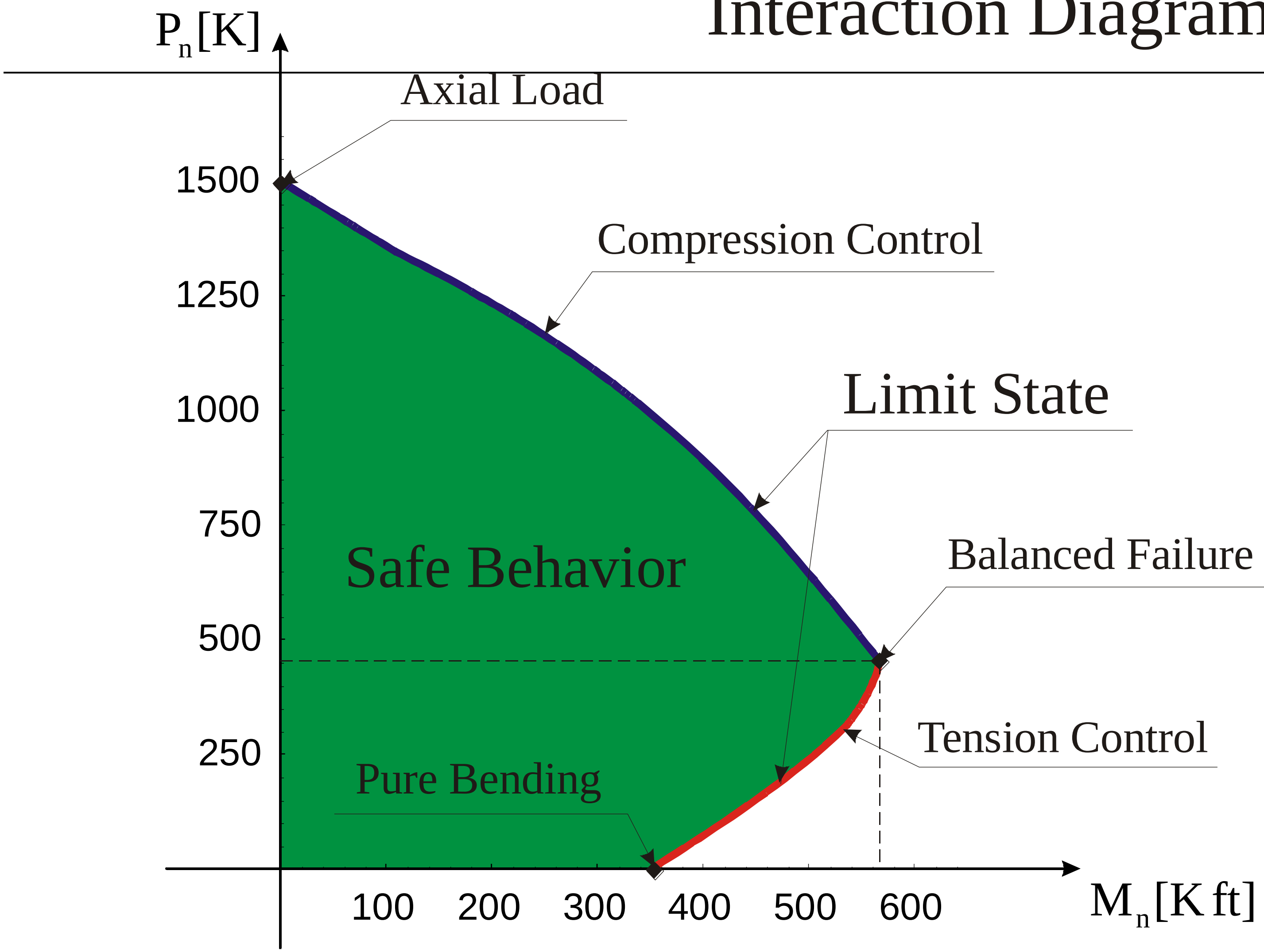
Eccentrically Loaded Columns

1. Basic Assumptions

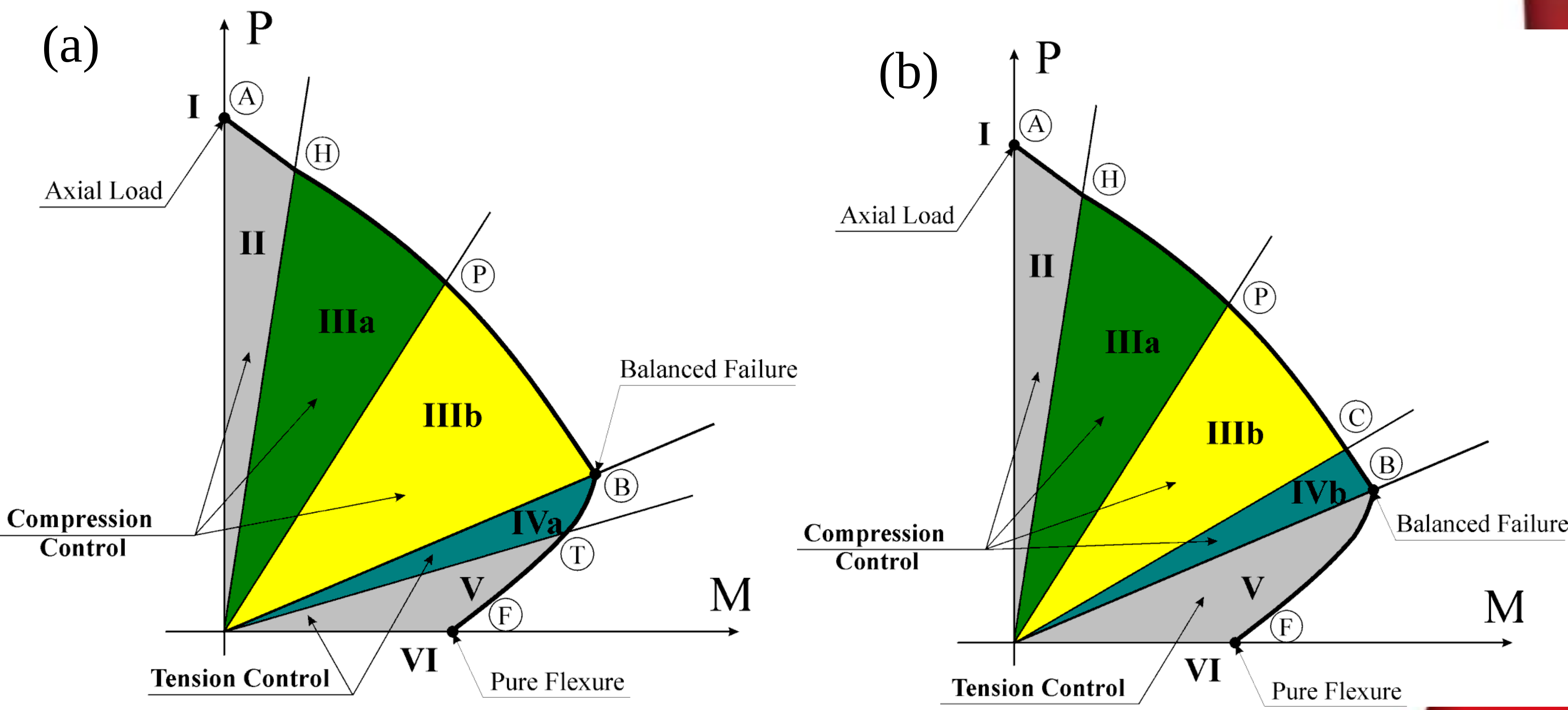


Columns

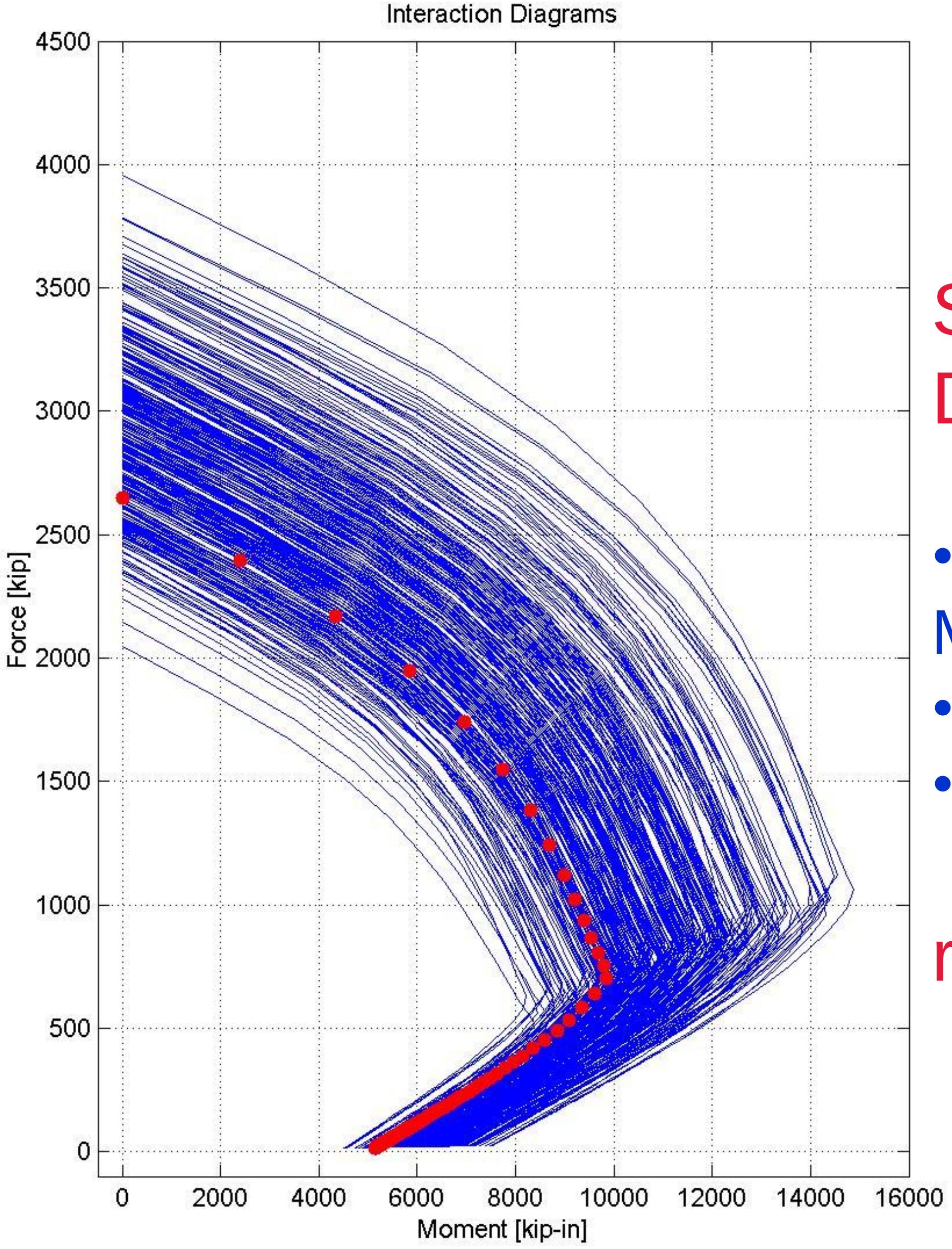
Interaction Diagram



Analysis of Possible Cases of Cross Section Behavior



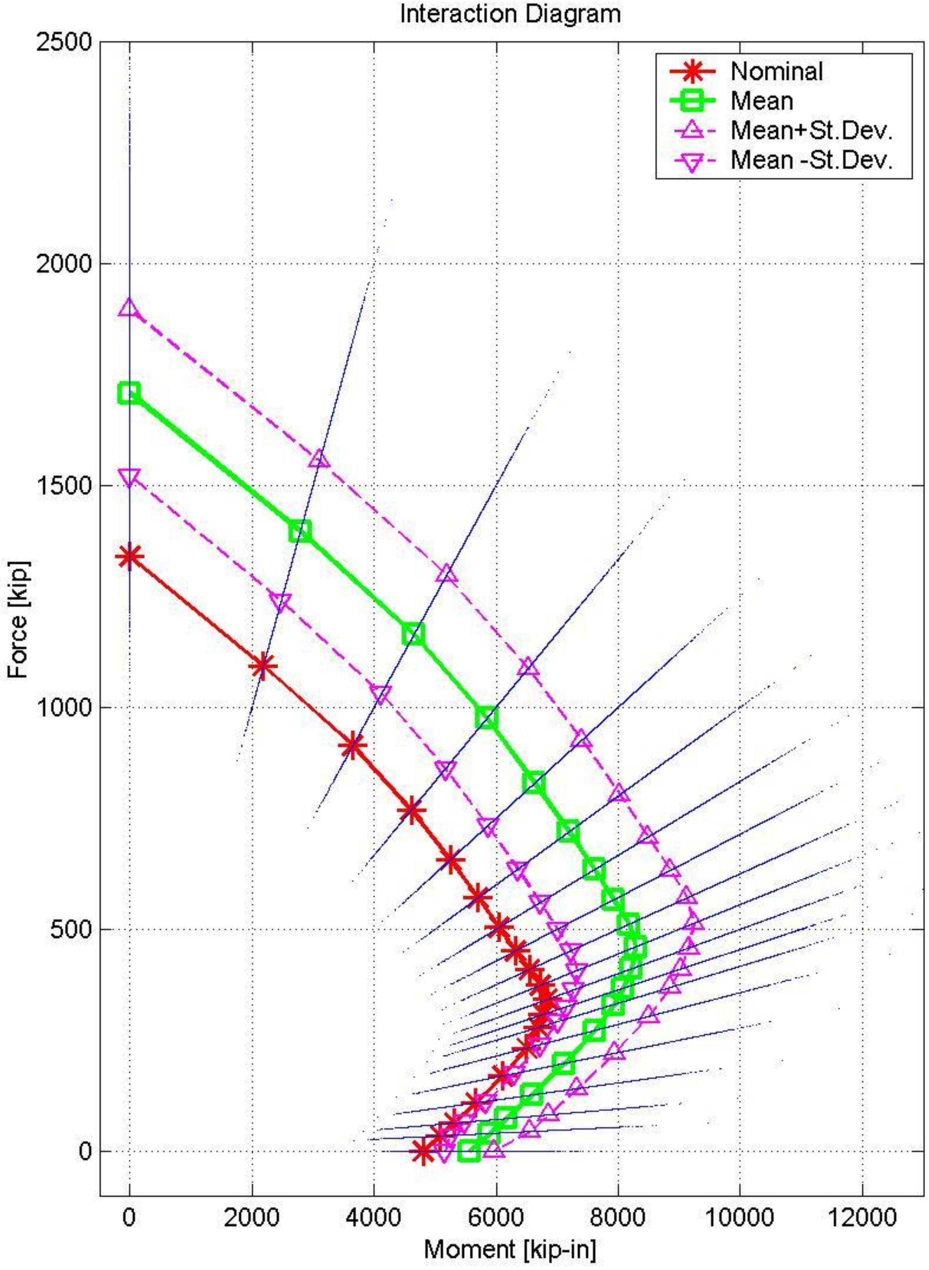
Interaction Diagram for Eccentrically Compressed Columns; (a) Cross Sections Type I, (b) Cross Sections Type II.



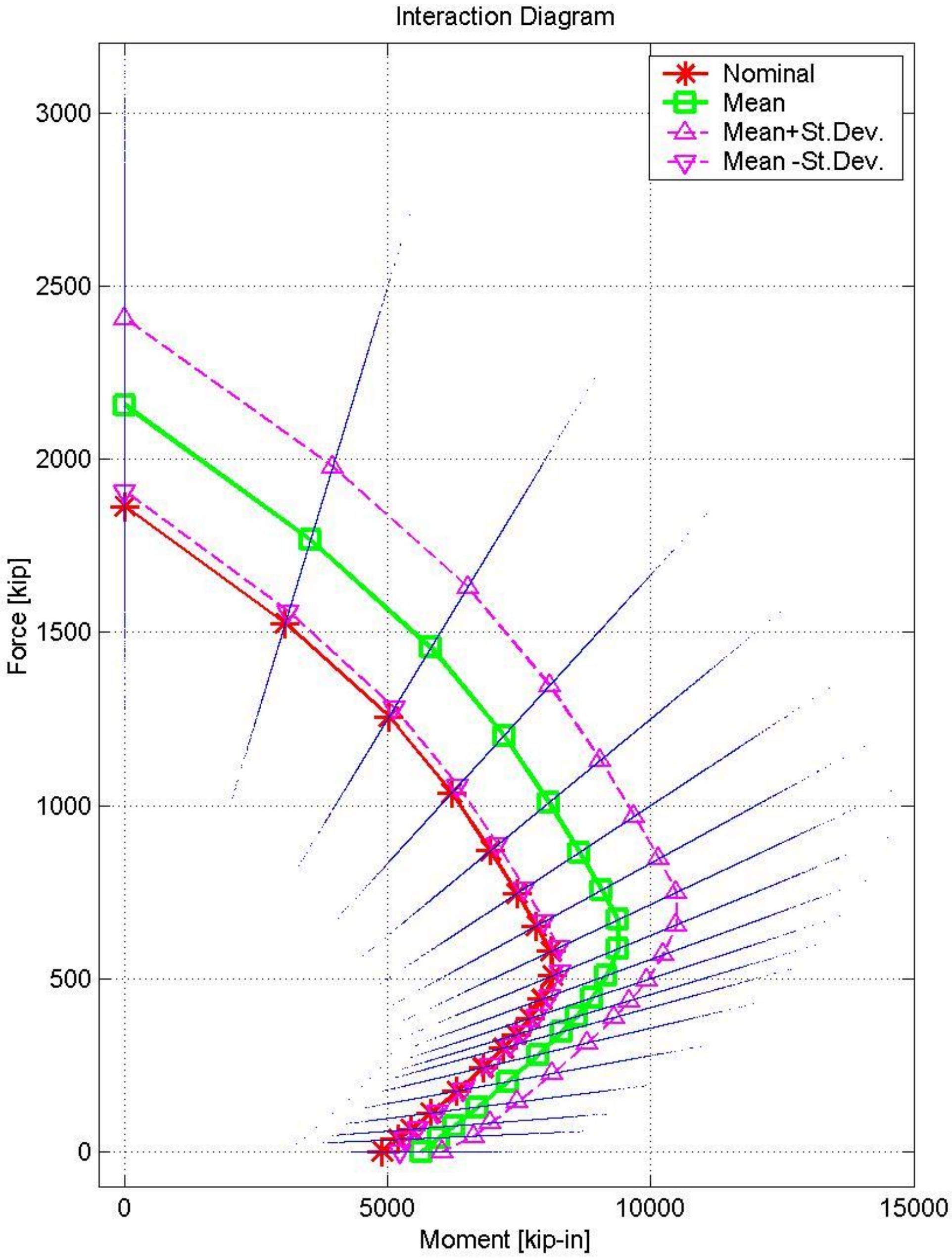
Simulated Interaction Diagrams

- concrete strength of 8 ksi (55 MPa)
- tied columns
- cast-in-place

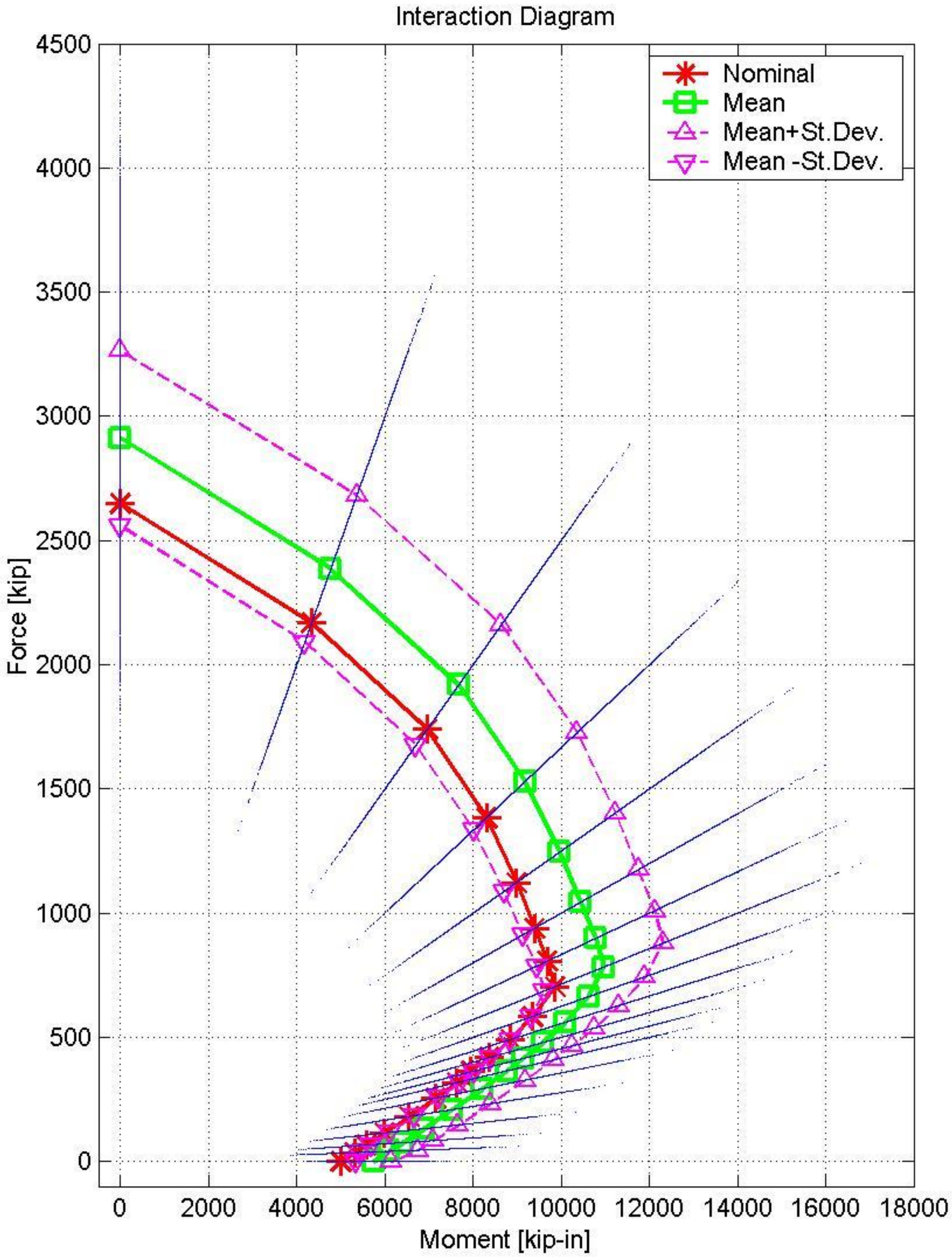
red dots = nominal values



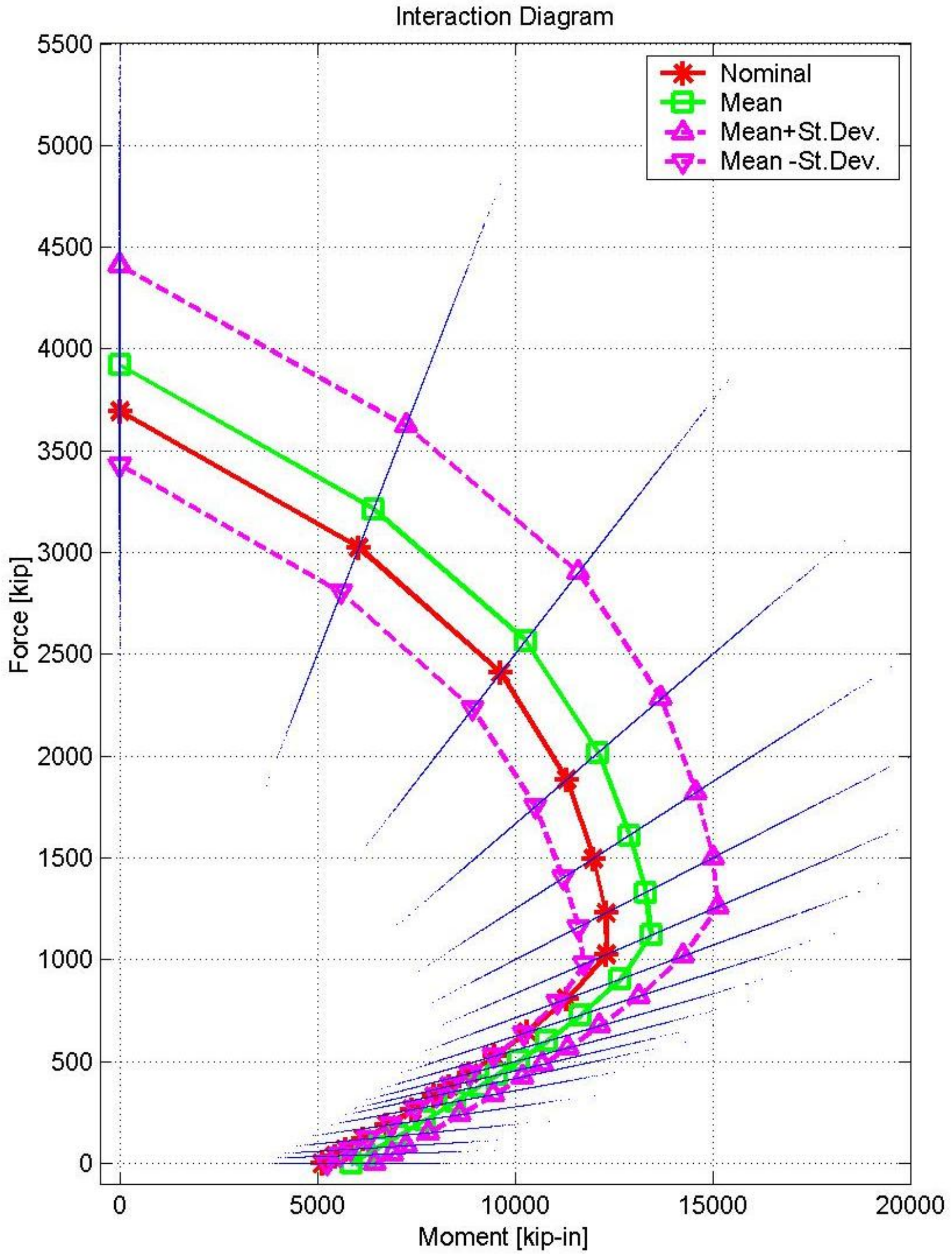
Interaction Diagrams
For Concrete 3 ksi (21 MPa)
(tied columns, cast-in-place)



Interaction Diagrams
For Concrete 5 ksi (35 MPa)
(tied columns, cast-in-place)



Interaction Diagrams
For Concrete 8 ksi (55 MPa)
(tied columns, cast-in-place)

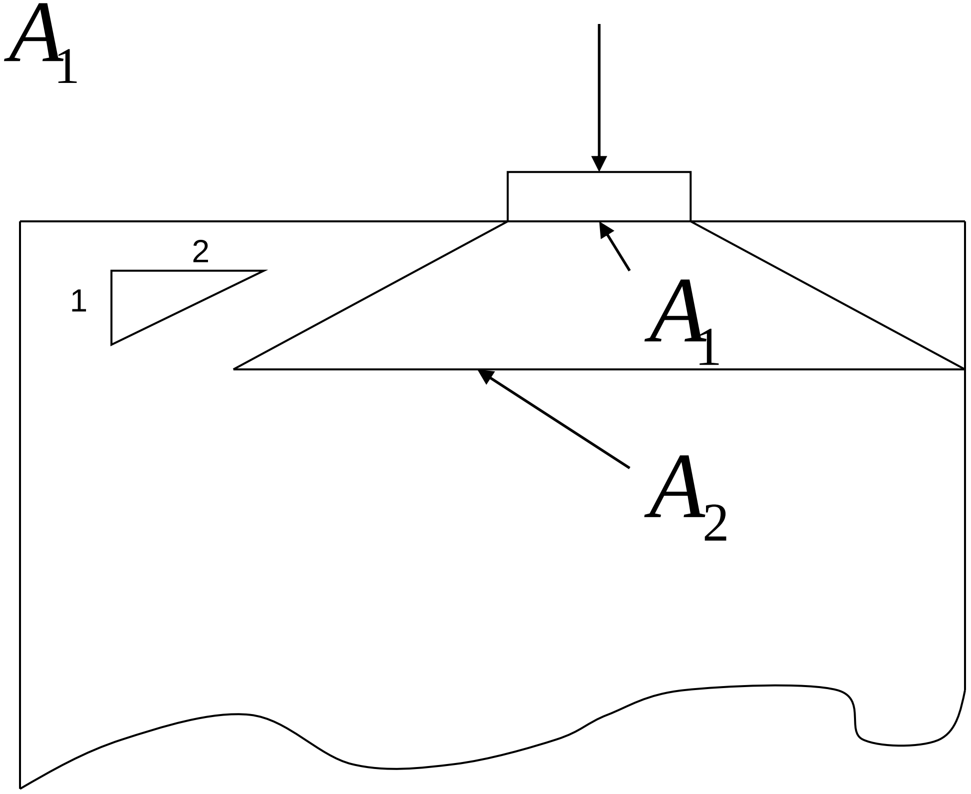


Interaction Diagrams

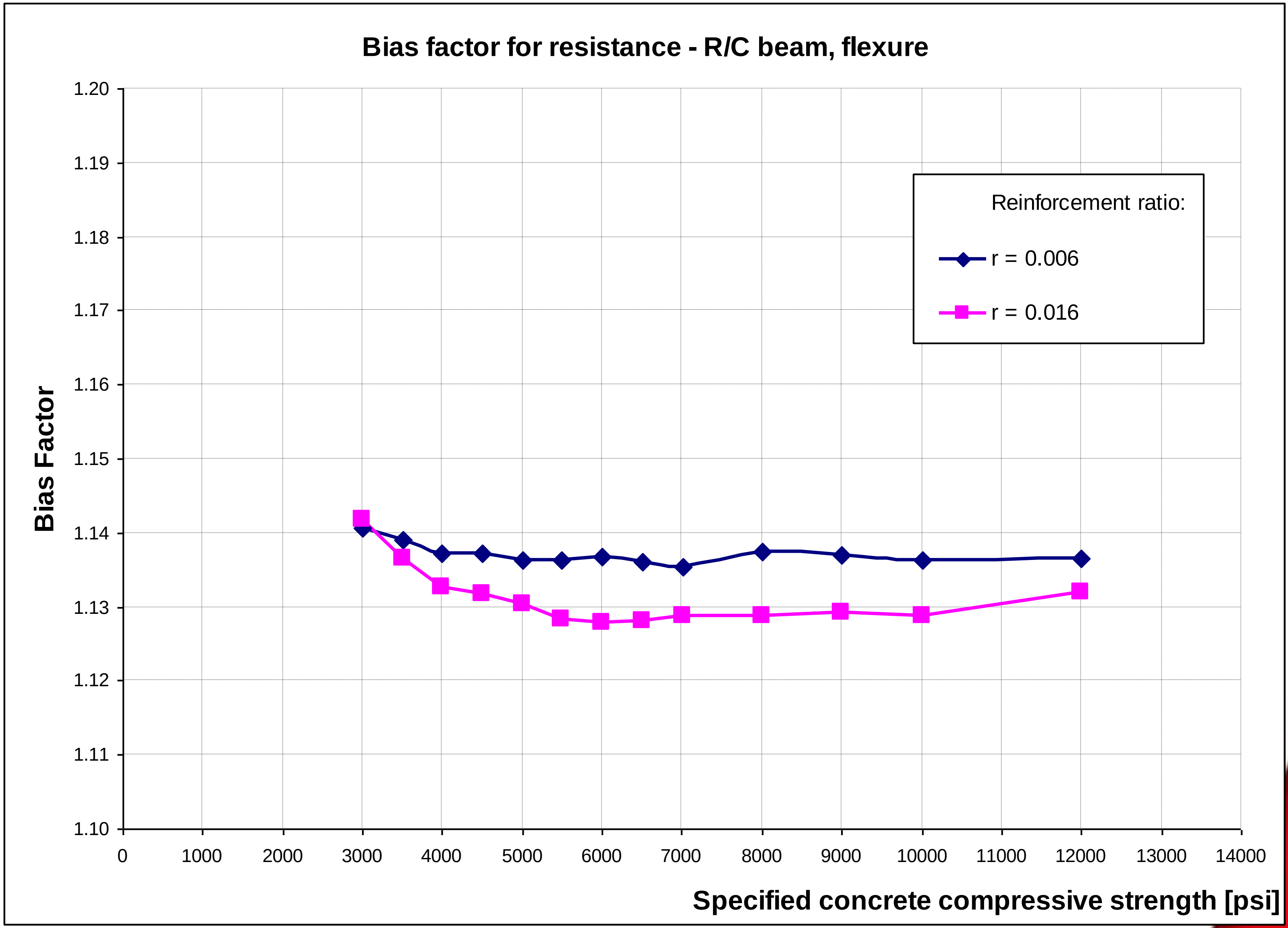
- concrete 12 ksi (85 MPa)
- tied columns,
- cast-in-place

Bearing Resistance of Concrete

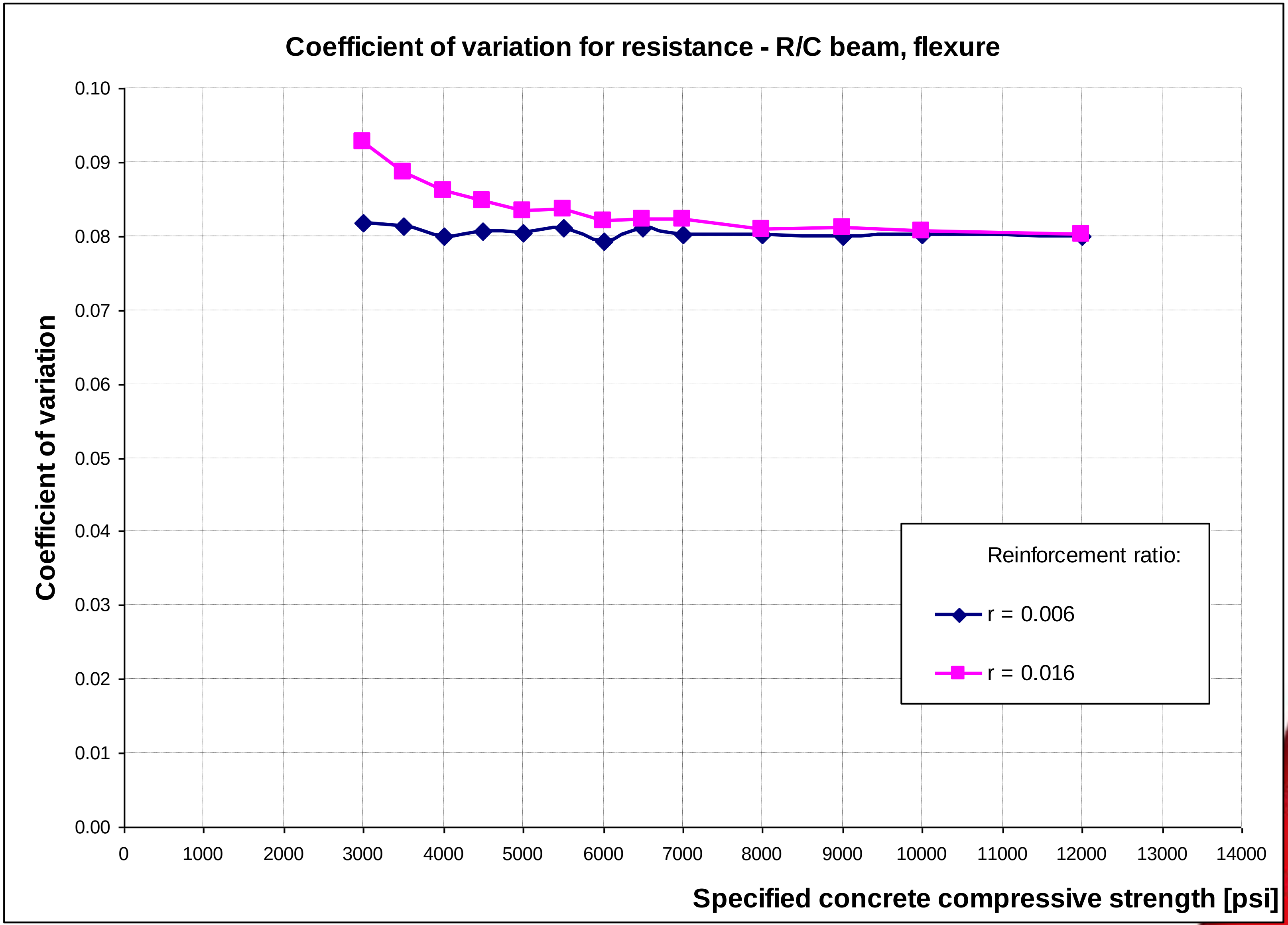
$$R = 0.85 f'_c A_1 \sqrt{\frac{A_2}{A_1}}$$



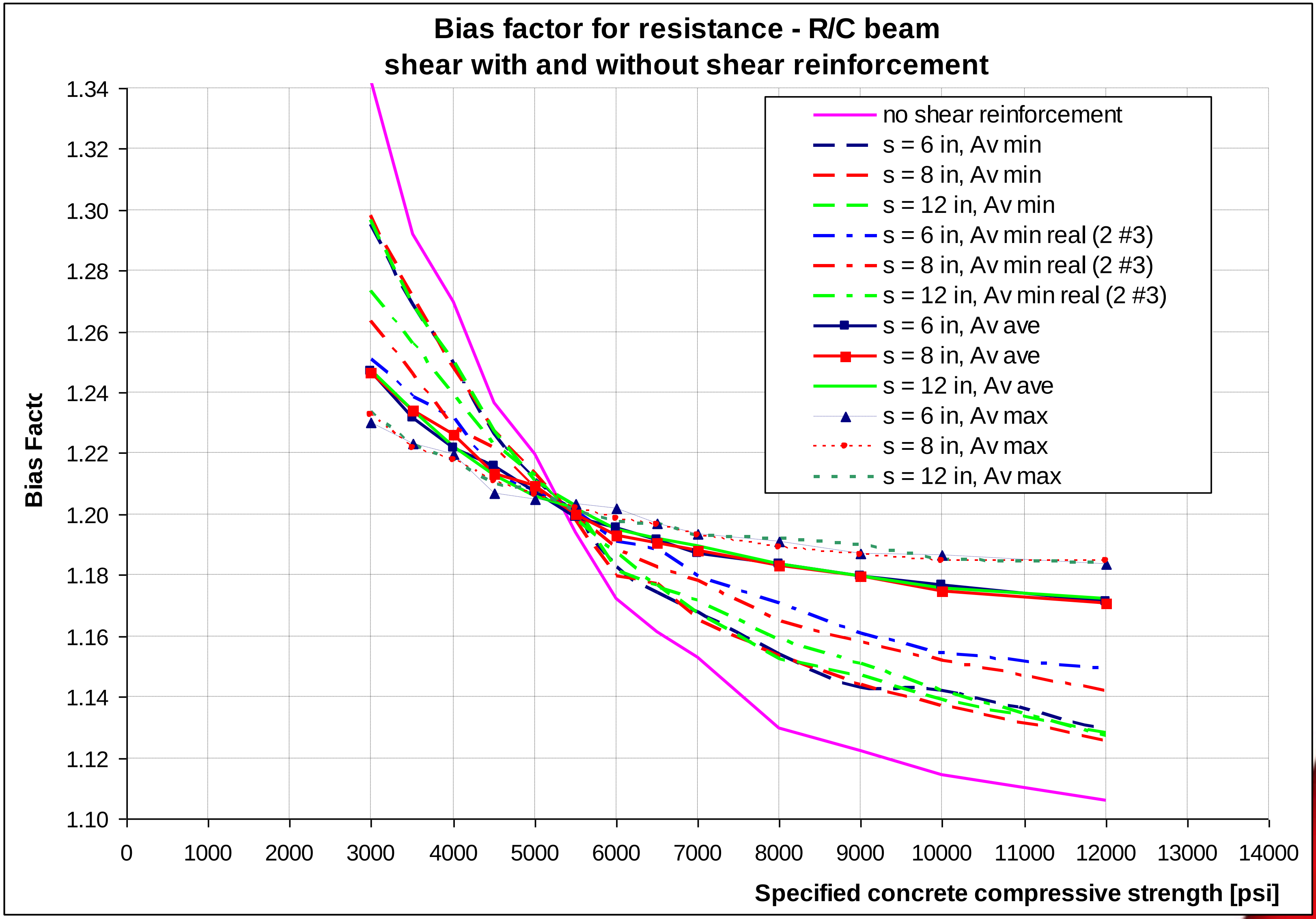
Bias Factor of Resistance for Beams, Flexure



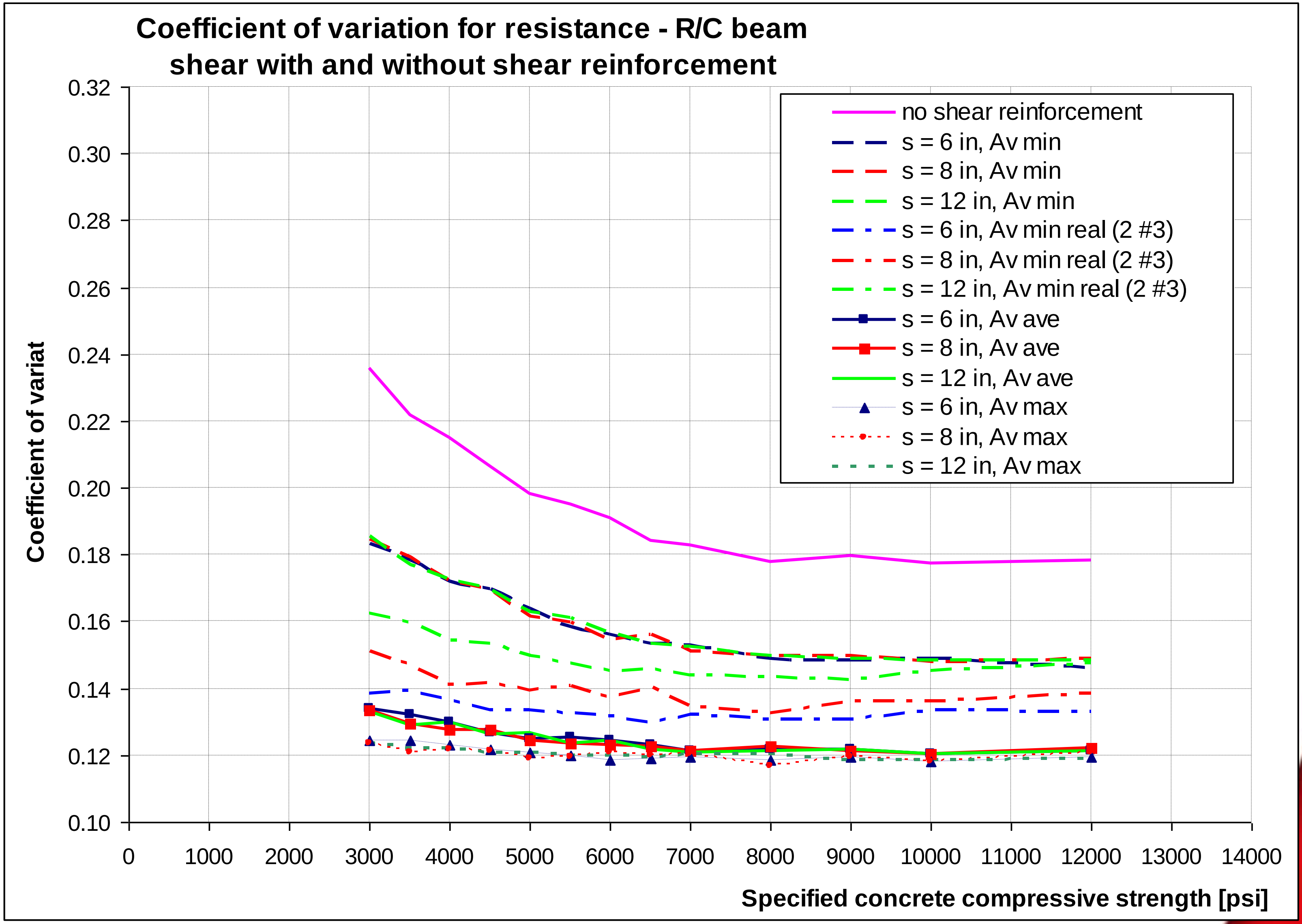
Coefficient of Variation of Resistance for Beams, Flexure



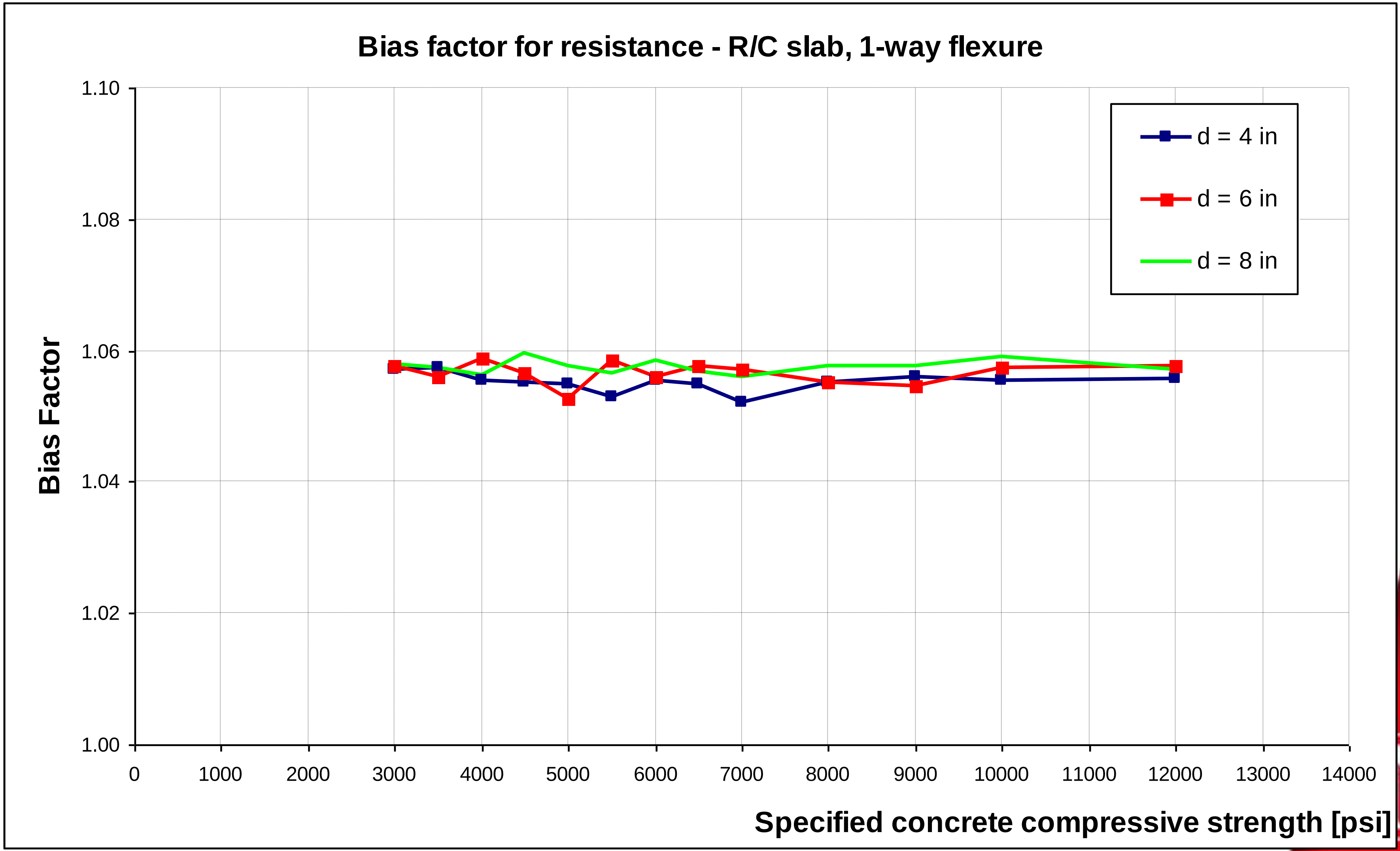
Bias Factor of Resistance for Beams, Shear



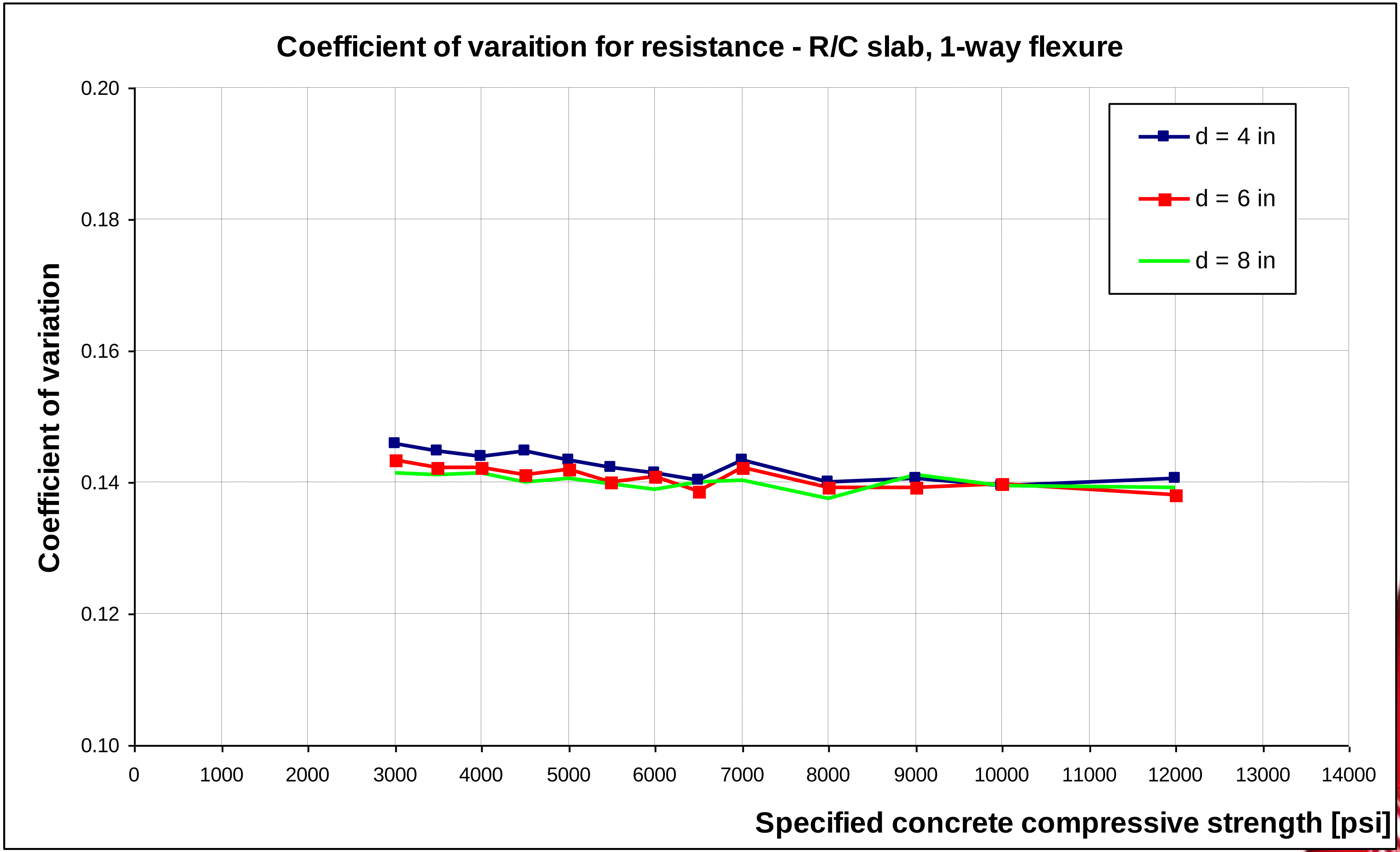
Coefficient of Variation of Resistance for Beams, Shear



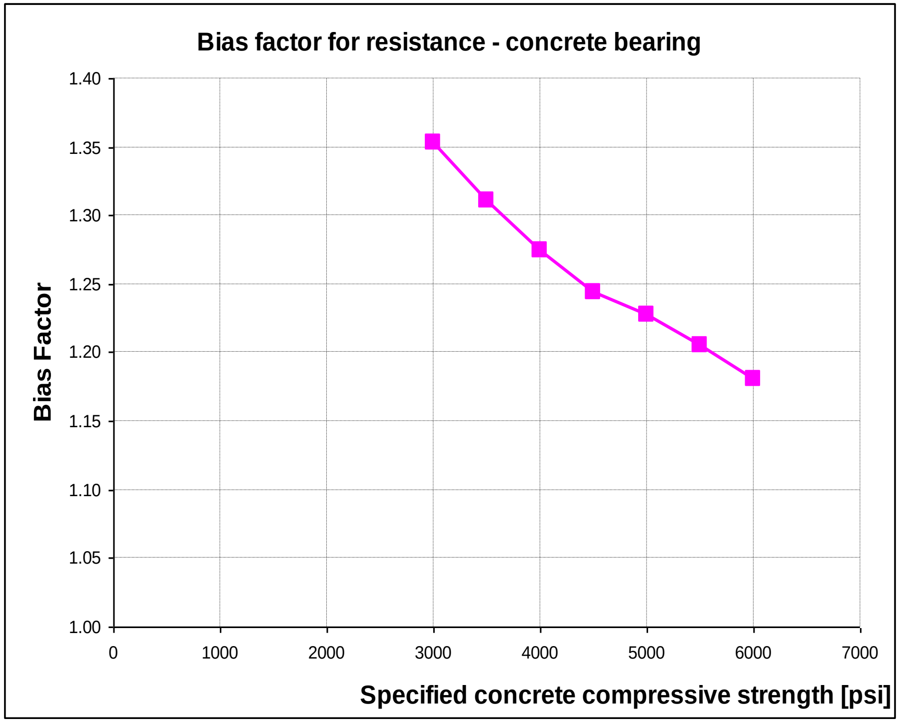
Bias Factor of Resistance for One way Slab, Flexure

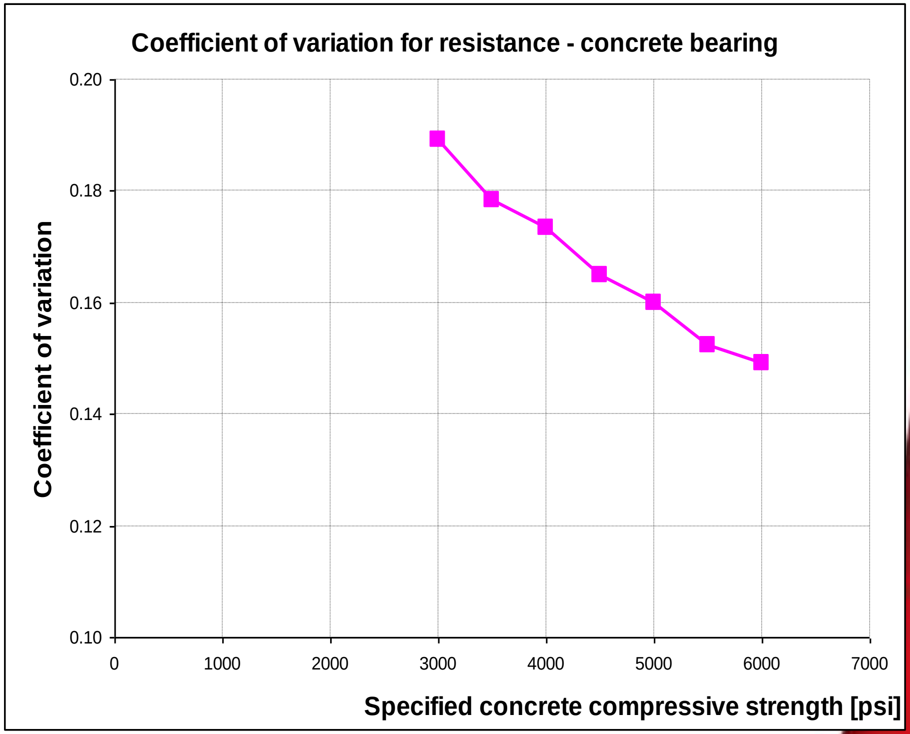


Coefficient of Variation of Resistance for One way slab, Flexure



Bias Factor and Coefficient of Variation of Resistance for Concrete Bearing Strength





Statistical Parameters of Fabrication Factor (Ellingwood, Galambos, MacGregor, Cornell)

	λ	V
width of beam, b	1.01	0.04
effective depth of beam, d	0.99	0.04
effective depth of one-way slab, d	0.92	0.12
effective depth of two-way slab, d		
d = 4 in	1.03	0.09
d = 6 in	1.02	0.06
d = 8 in	1.015	0.04
depth and width of column, b_1, b_2	1.005	0.04
area of reinforcement, A_s, A_v	1.00	0.015
spacing of shear reinforcement, s	1.00	0.04

Statistical Parameters of Professional Factor (Ellingwood, Galambos, MacGregor, Cornell)

	λ	V
R/C beams - flexure	1.02	0.06
R/C beams - shear without stirrups	1.16	0.11
R/C beams - shear with stirrups	1.075	0.10
Axially loaded columns, tied	1.00	0.08
Axially loaded columns, spiral	1.05	0.06
One way slabs - flexure	1.02	0.06
One way slabs - shear	1.16	0.11
Two way slabs - shear	1.16	0.11
Bearing strength	1.02	0.06

Monte Carlo Simulation Results - Examples

Resistance parameters for concrete $f_c' = 4000$ psi (28 MPa)

	λ	V
R/C beams - flexure	1.14	0.08
R/C beams - shear without stirrups	1.27	0.23
R/C beams - shear with stirrups	1.235	0.15
Axially loaded columns, tied	1.22	0.145
Axially loaded columns, spiral	1.29	0.14
One way slabs - flexure	1.055	0.14
One way slabs - shear	1.165	0.255
Two way slabs - shear	1.305	0.24
Bearing strength	1.275	0.17

Basic questions:

- How can we measure safety of a structure?
- How safe is safe enough? What is the target reliability?
- How to implement the optimum safety level?

Reliability Index, β

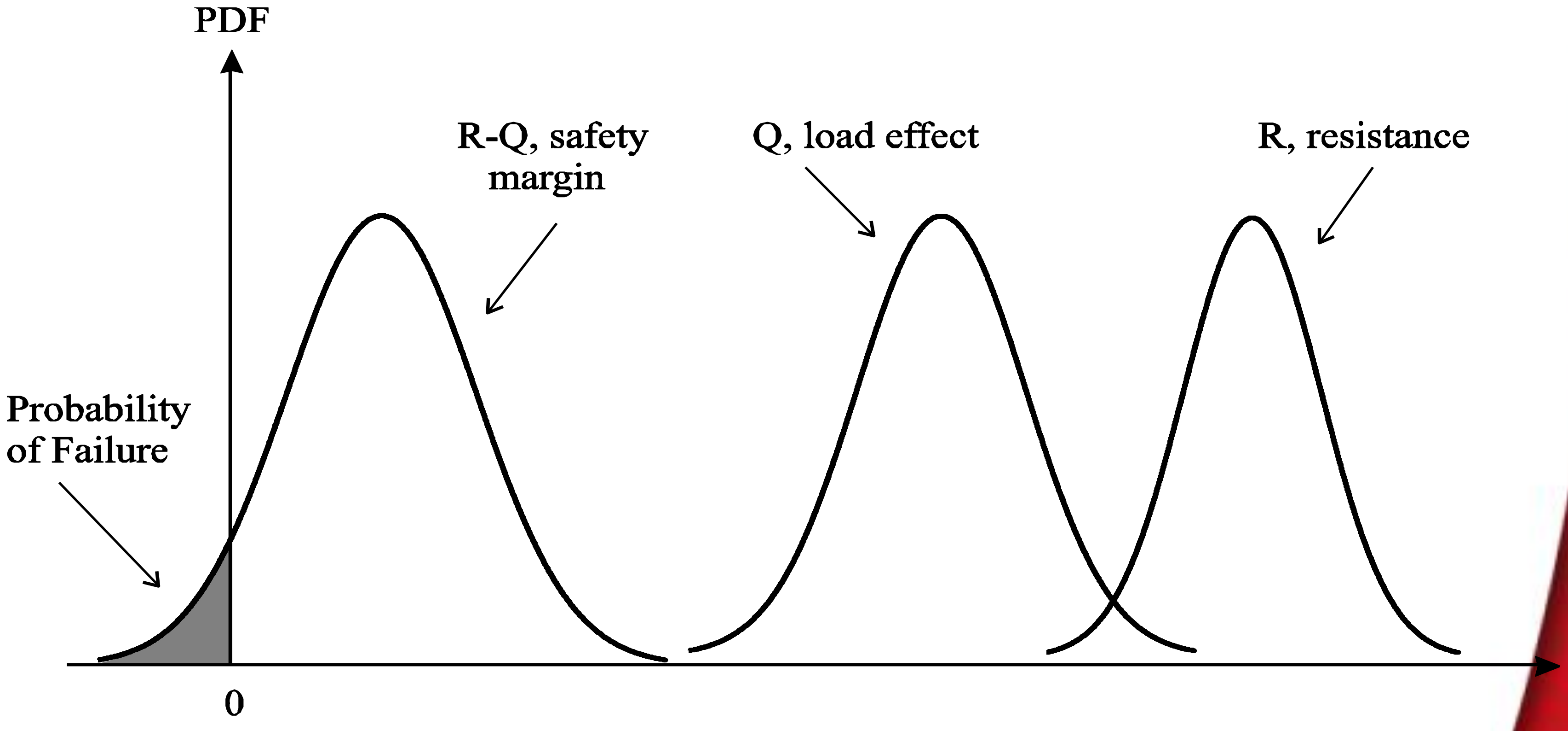


Figure 5-8 PDFs of load, resistance, and safety margin.

Reliability Index, β

For a linear limit state function, g = R – Q = 0, and R and Q both being normal random variables

$$\beta = \frac{(\mu_R - \mu_Q)}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

μ_R = mean resistance
μ_Q = mean load
σ_R = standard deviation of resistance
σ_Q = standard deviation of load

Reliability index and probability of failure

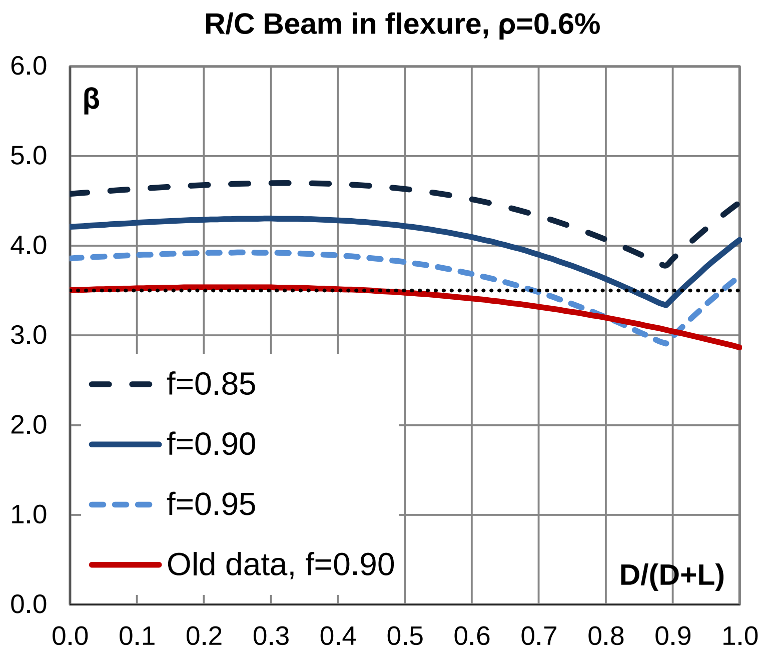
P_F	β
10^{-1}	1.28
10^{-2}	2.33
10^{-3}	3.09
10^{-4}	3.71
10^{-5}	4.26
10^{-6}	4.75
10^{-7}	5.19
10^{-8}	5.62
10^{-9}	5.99

Reliability Analysis Procedures

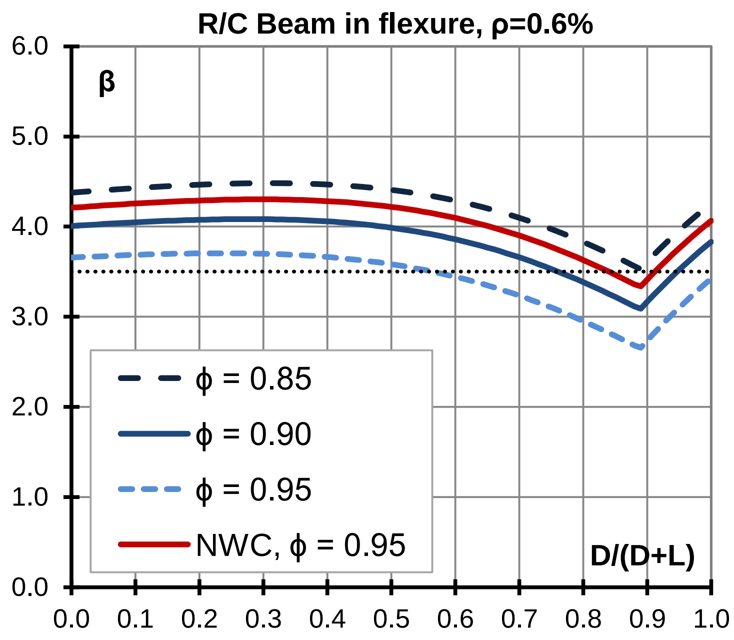
- Closed-form equations – accurate results only for special cases
- First Order Reliability Methods (FORM), reliability index is calculated by iterations
- Second Order Reliability Methods (SORM), and other advanced procedures
- Monte Carlo method - values of random variables are simulated (generated by computer), accuracy depends on the number of computer simulations

Reliability Indices for R/C Beams, Flexure, (D+L)

Ordinary concrete

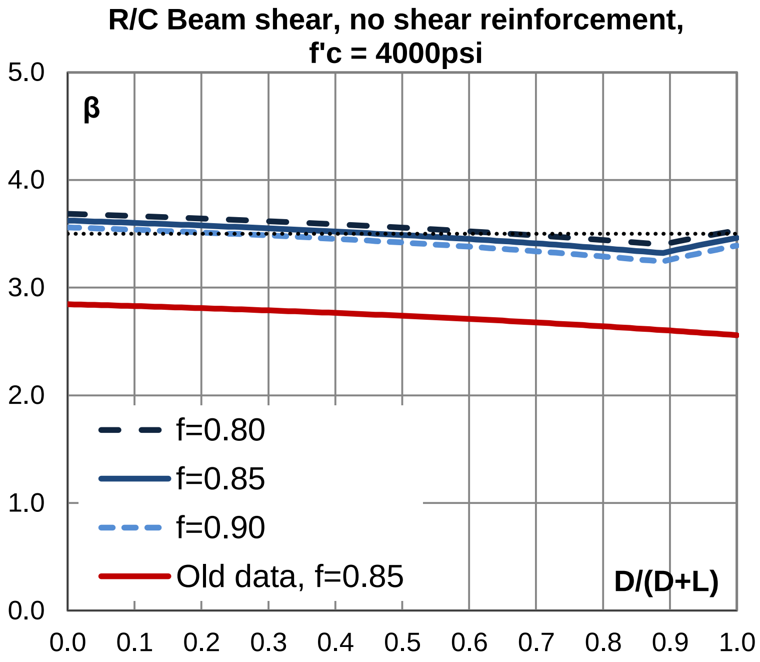


Lightweight concrete

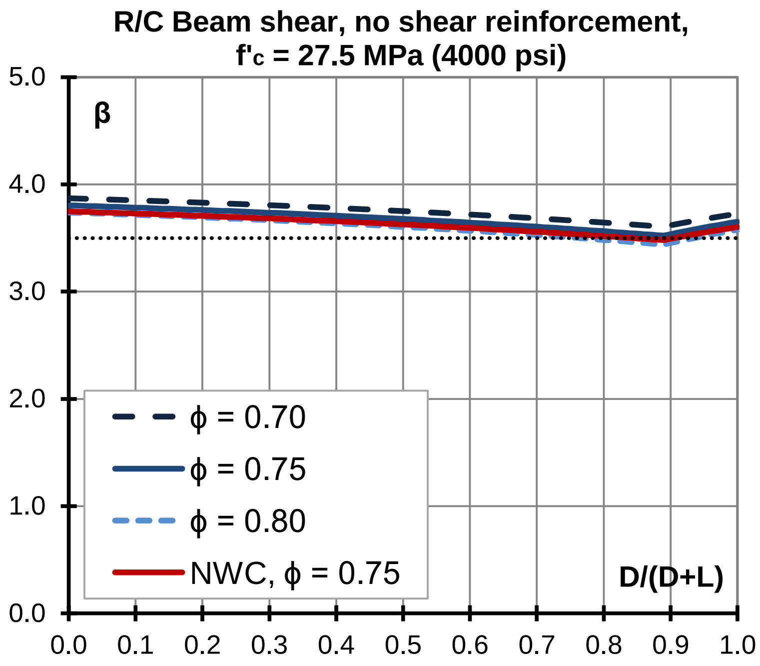


Reliability Indices for R/C Beams, Shear, (D+L)

Ordinary concrete

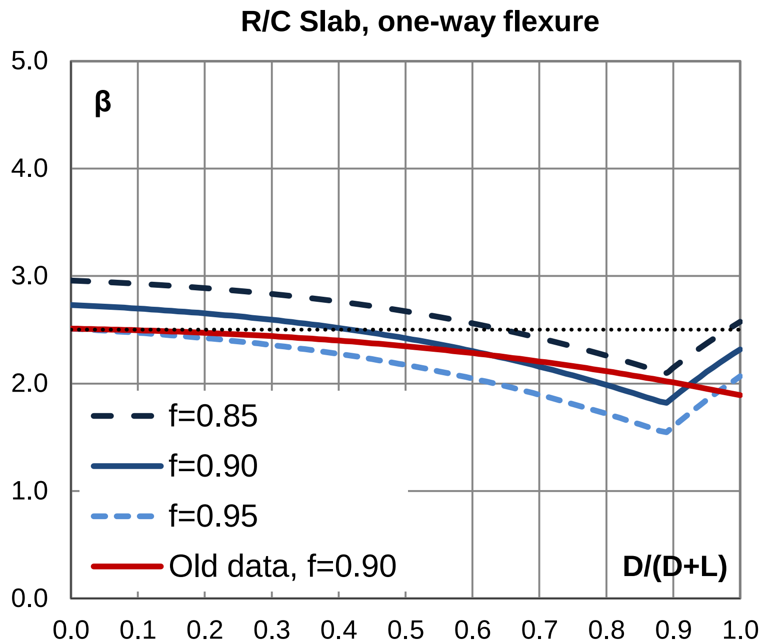


Lightweight concrete

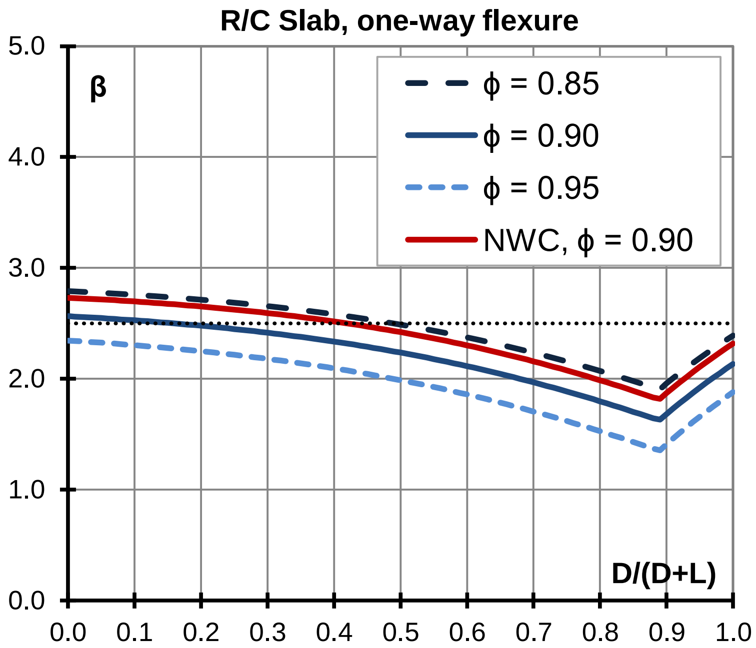


Reliability Indices for R/C Slab, flexure, (D+L)

Ordinary concrete

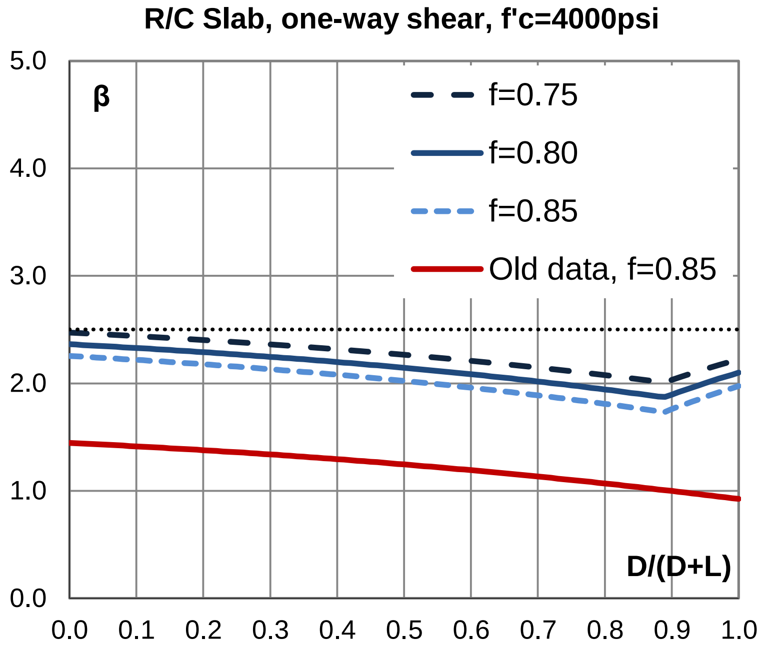


Lightweight concrete

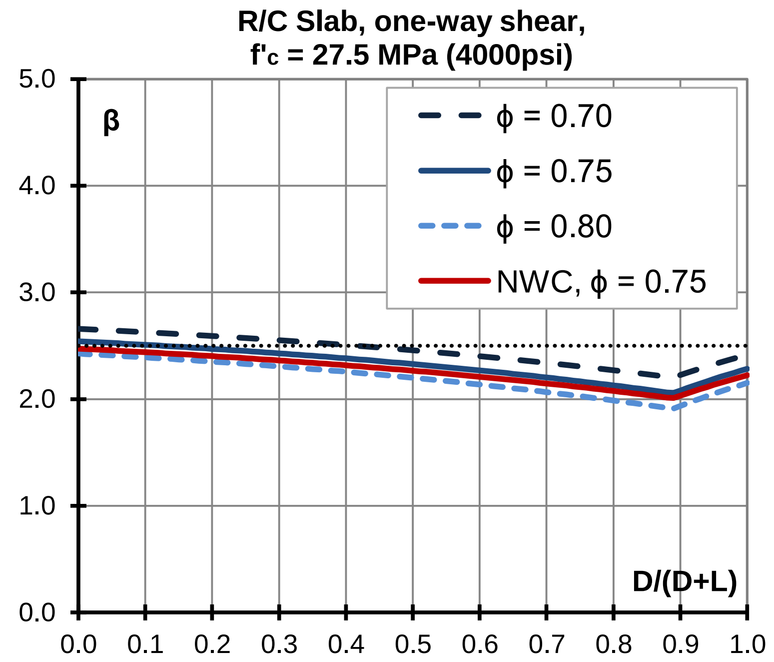


Reliability Indices for R/C Slab, one-way shear, (D+L)

Ordinary concrete

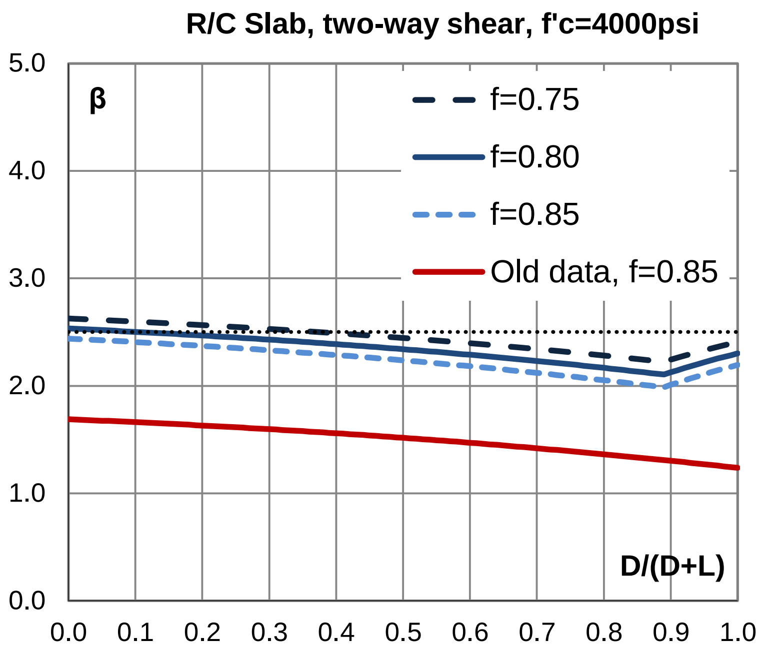


Lightweight concrete

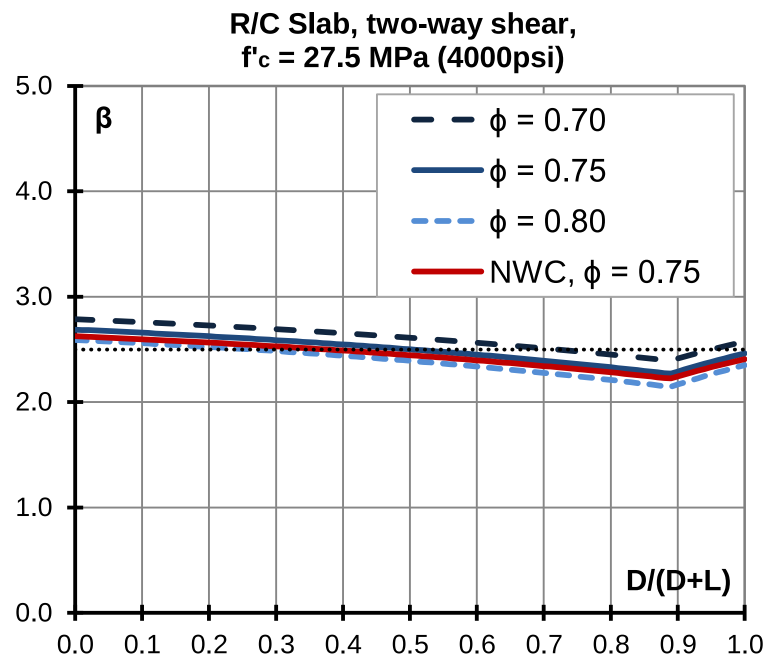


Reliability Indices for R/C Slab, two-way shear, (D+L)

Ordinary concrete

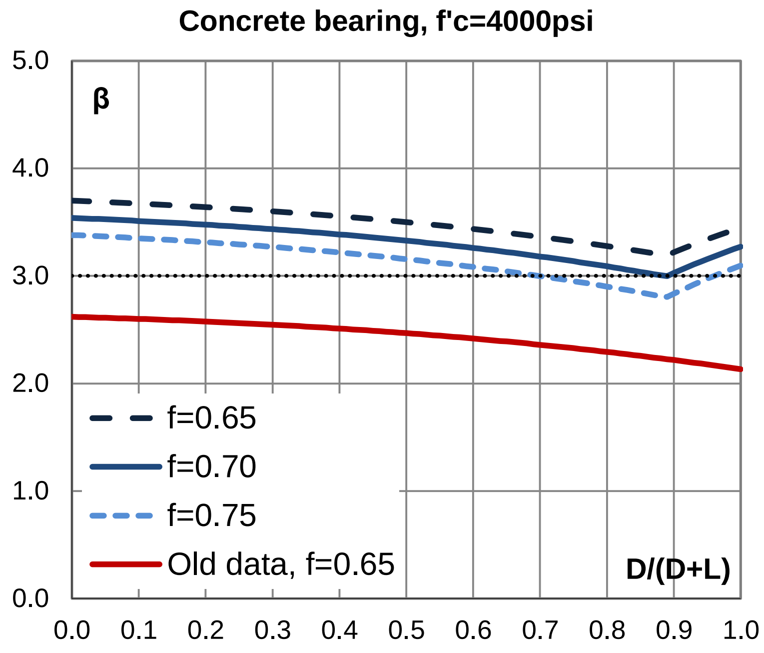


Lightweight concrete

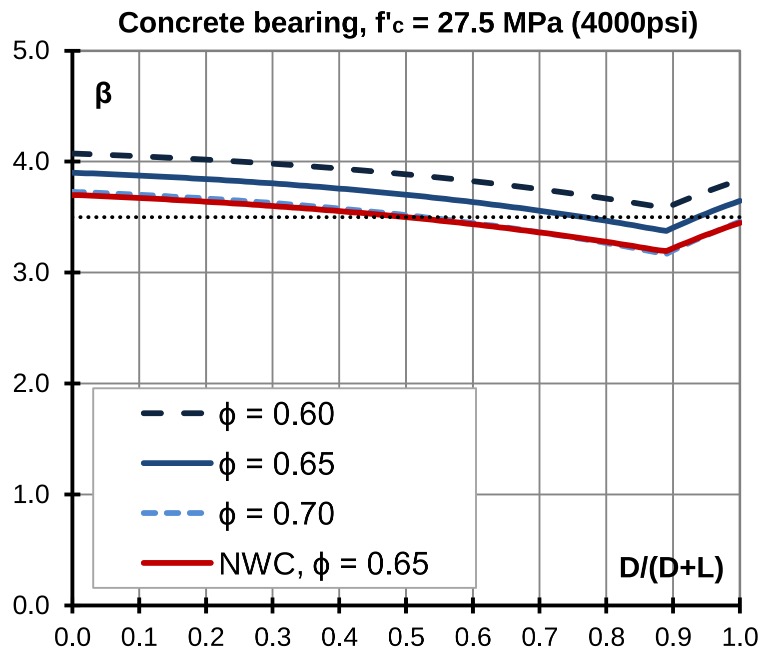


Reliability Indices for Concrete bearing, (D+L)

Ordinary concrete



Lightweight concrete



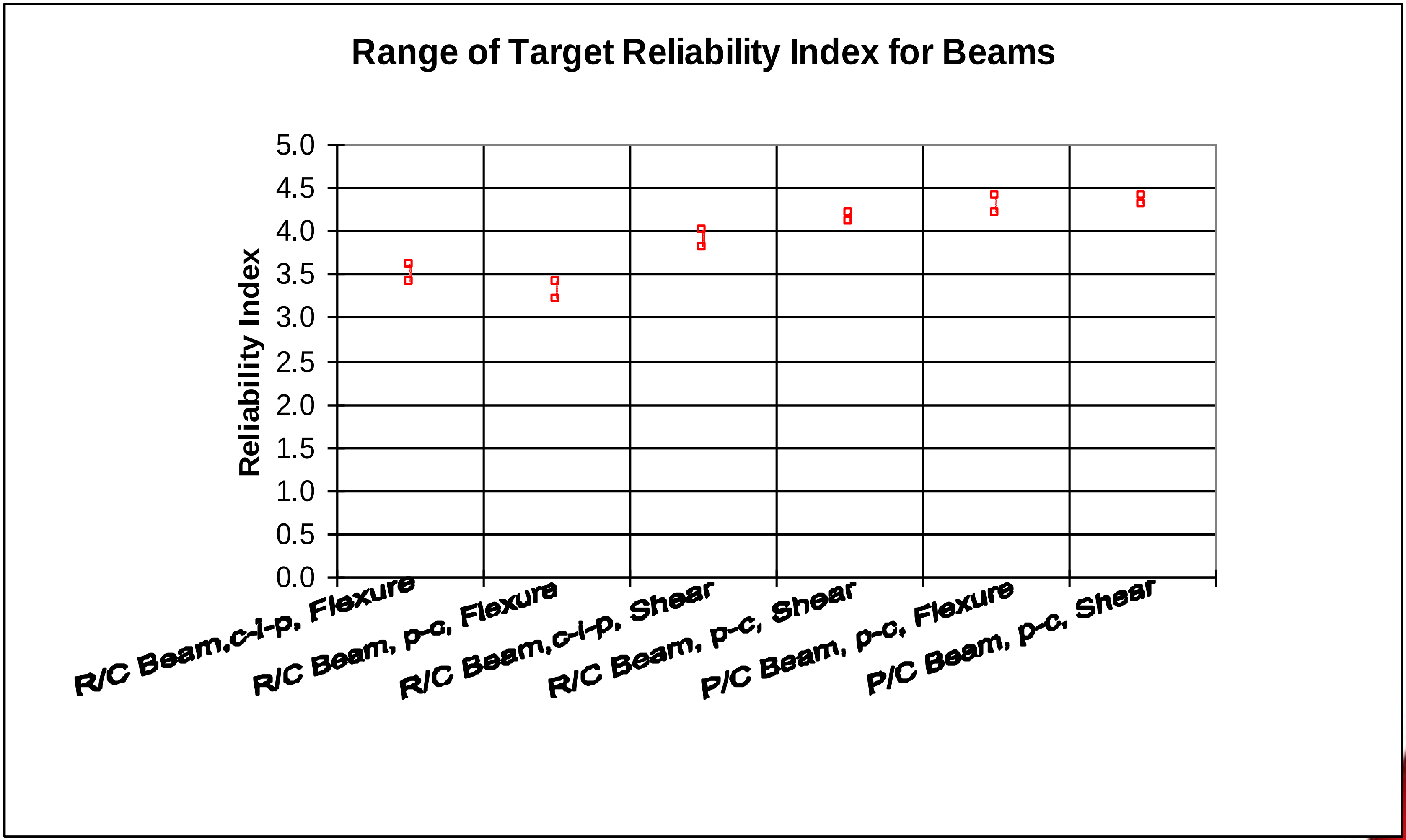
What is Optimum Reliability?

- If reliability index is too small – there are problems, even structural failures
- If reliability index is too large – the structures are too expensive

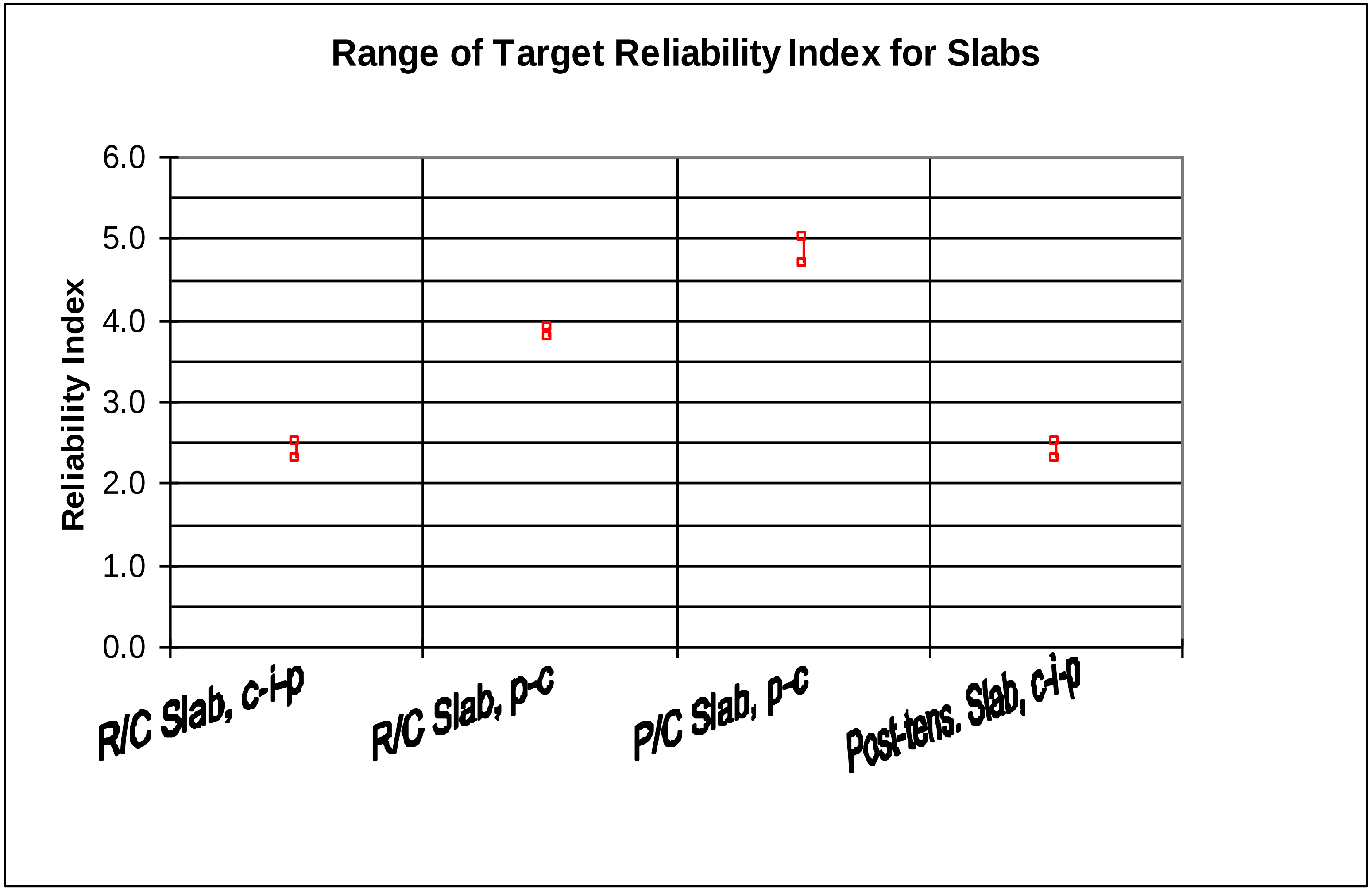
Target Reliability

- Consequences of failure
- Economic analysis
- Past practice
- Human perception
- Social/political decisions

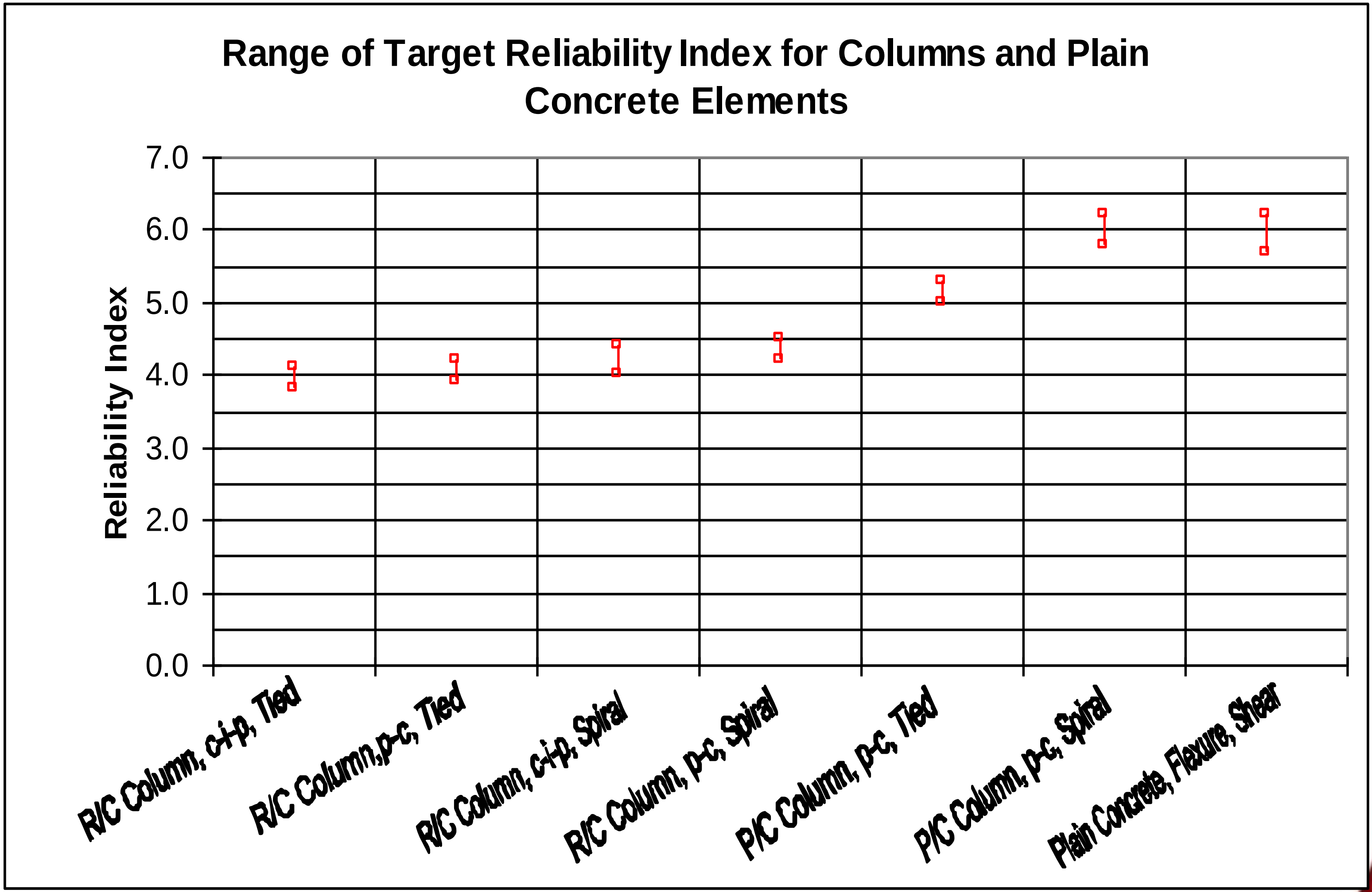
Selected Range of Reliability Indices for Beams, designed according to “old” ACI 318



Selected Range of Reliability Indices for Slabs, designed according to “old” ACI 318



Selected Range of Reliability Indices for Columns and Plain Concrete Elements, designed according to "old" ACI 318



Calibration Results

	ACI 318-99	ACI 318-05	Recommended	
	ϕ	ϕ	ϕ	β_T
• R/C beams – flexure	0.90	0.90	0.90	3.5
• R/C beams - shear w/o stirrups	0.85	0.75	0.85	2.5
• R/C beams - shear with stirrups	0.85	0.75	0.85	3.5
• Axially loaded columns, tied	0.70	0.65	0.70	4.0
• Axially loaded columns, spiral	0.75	0.70	0.75	4.0
• One way slabs – flexure	0.90	0.90	0.90	2.5
• One way slabs – shear	0.85	0.75	0.85	2.5
• Two way slabs – shear	0.85	0.75	0.85	2.5
• Bearing strength	0.70	0.65	0.70	3.0

Load factors specified by ACI 318 and ASCE 7

The design formula specified by ACI 318-99 Code

$1.4 D + 1.7 L < \phi R$

$0.75 (1.4 D + 1.7 L + 1.7 W) < \phi R$

$0.9 D + 1.3 W < \phi R$

$0.75 (1.4 D + 1.7 L + 1.87 E) < \phi R$

The design formula specified by ASCE-7 Standard

$1.4 D < \phi R$

$1.2 D + 1.6 L < \phi R$

$1.2 D + 1.6 L + 0.5 S < \phi R$

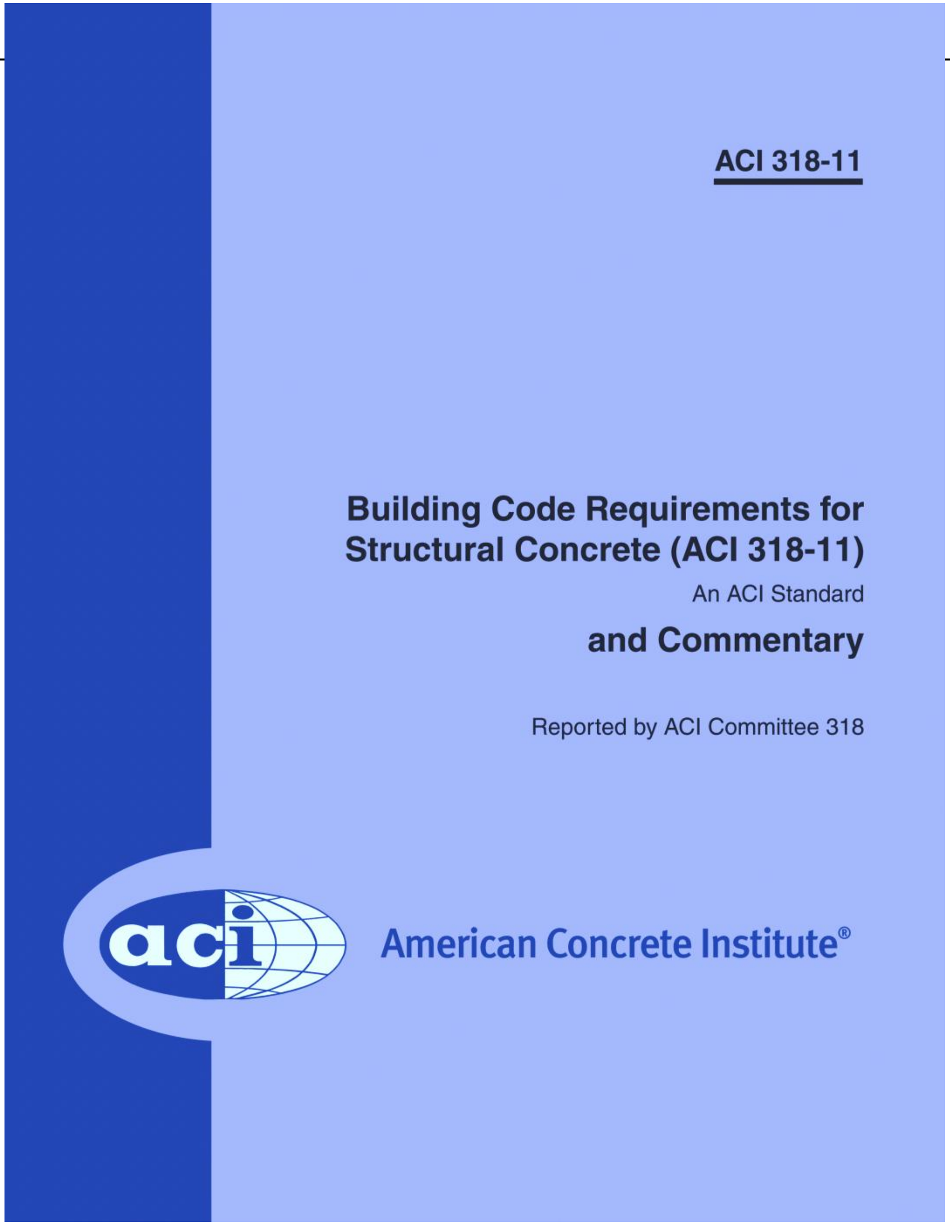
$1.2 D + 0.5 L + 1.6 S < \phi R$

$1.2 D + 1.6 W + 0.5 L + 0.5 S < \phi R$

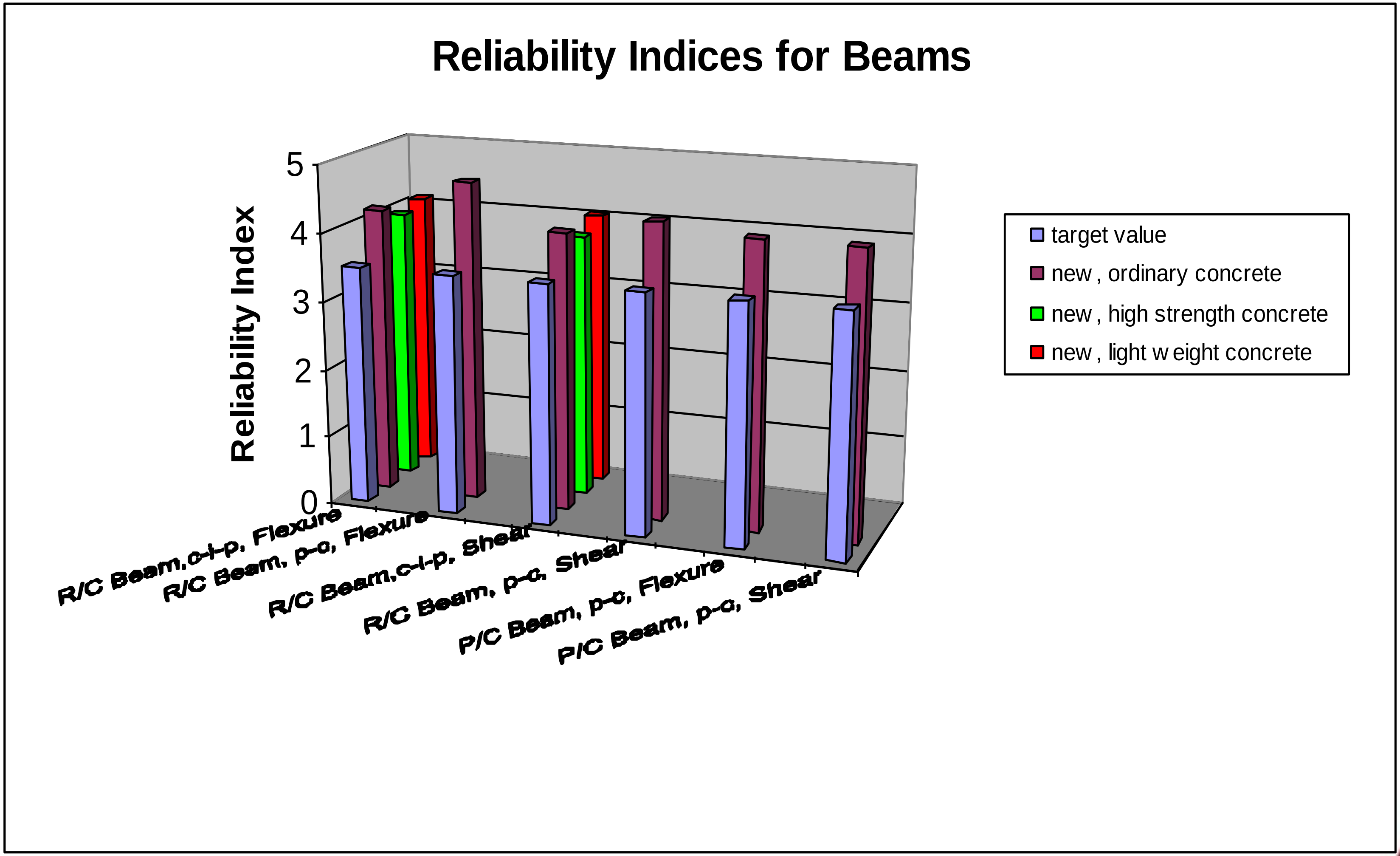
$1.2 D + 1.0 E + 0.5 L + 0.2 S < \phi R$

$0.9 D – (1.6 W \text{ or } 1.0 E) < \phi R$

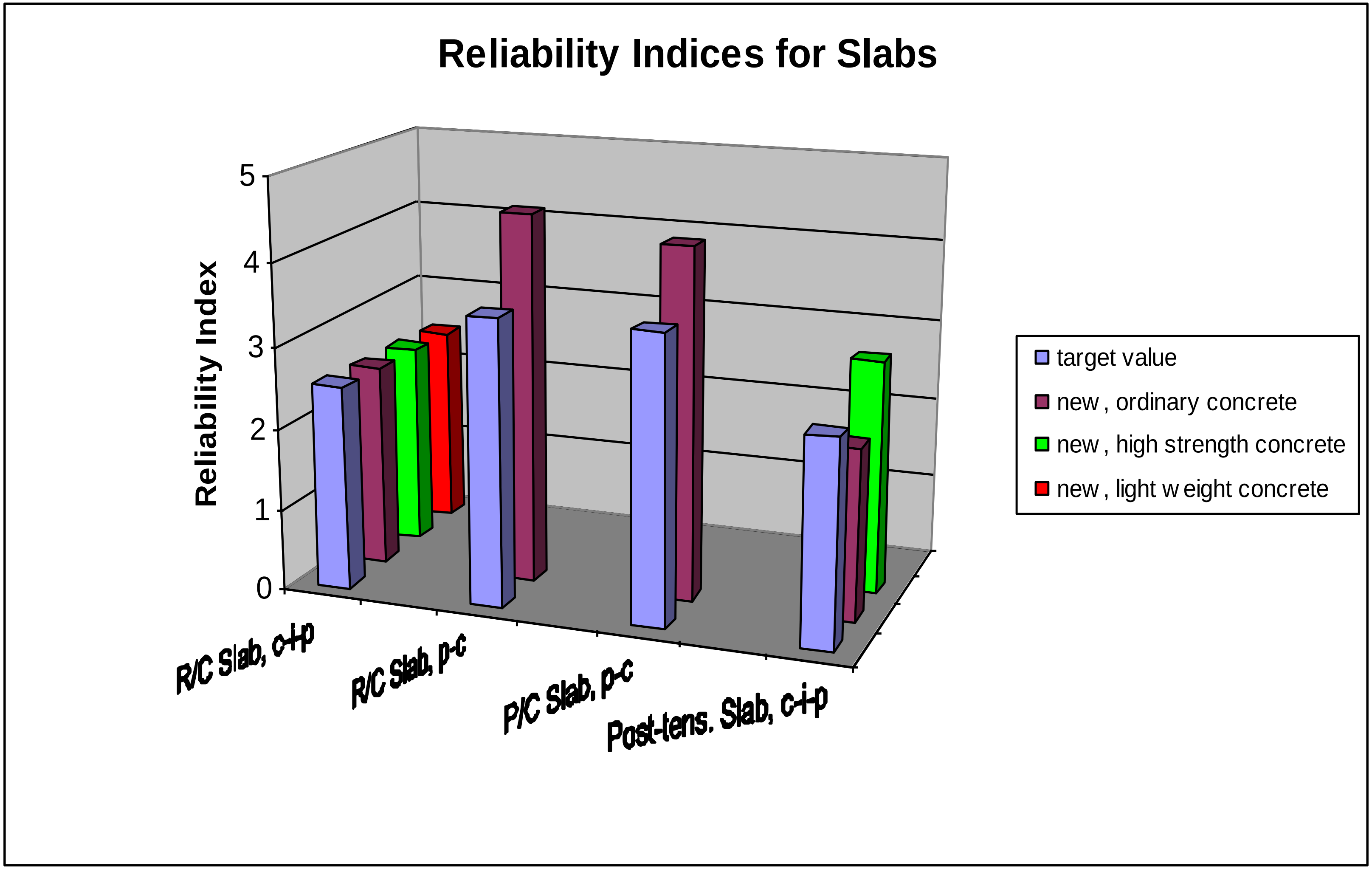
American Concrete Institute (ACI)



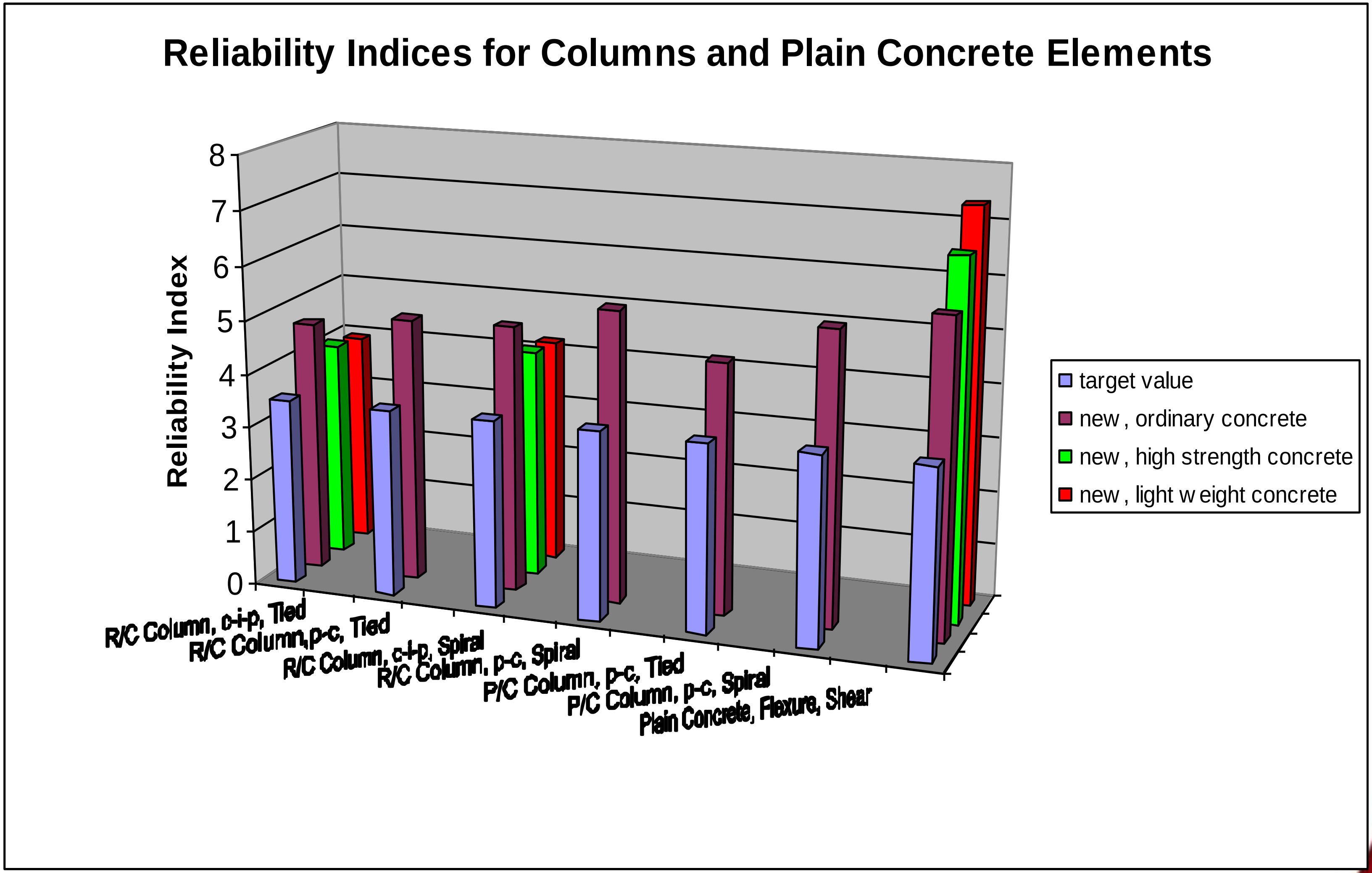
Reliability Indices for Beams, designed according to the “new” ACI 318



Reliability Indices for Slabs, designed according to the “new” ACI 318



Reliability Indices for Columns and Plain Concrete Elements, designed according to the "new" ACI 318



Load factors specified by ACI 318 and Proposed Design Formula

The design formula specified by ACI 318-99 Code

$1.4\ D + 1.7\ L < \phi R$

$0.75\ (1.4\ D + 1.7\ L + 1.7\ W) < \phi R$

$0.9\ D + 1.3\ W < \phi R$

$0.75\ (1.4\ D + 1.7\ L + 1.87\ E) < \phi R$

Proposed design formula

$1.4\ (D + L) < \phi R$

$1.2\ D + 1.6\ L < \phi R$

$1.2\ D + 1.6\ L + 0.5\ S < \phi R$

$1.2\ D + 0.5\ L + 1.6\ S < \phi R$

$1.2\ D + 1.6\ W + 0.5\ L + 0.5\ S < \phi R$

$1.2\ D + 1.0\ E + 0.5\ L + 0.2\ S < \phi R$

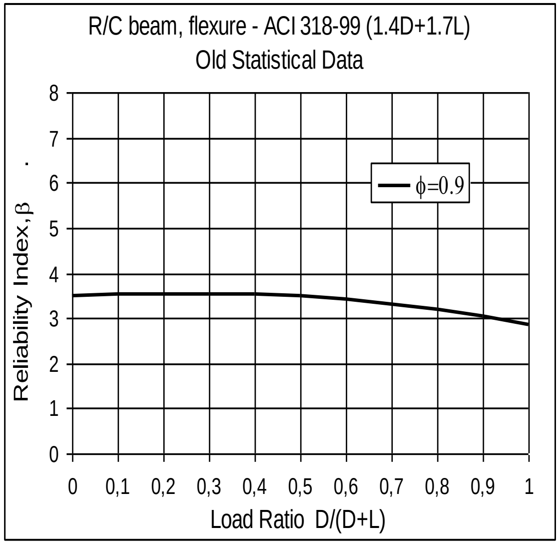
$0.9\ D – (1.6\ W \text{ or } 1.0\ E) < \phi R$

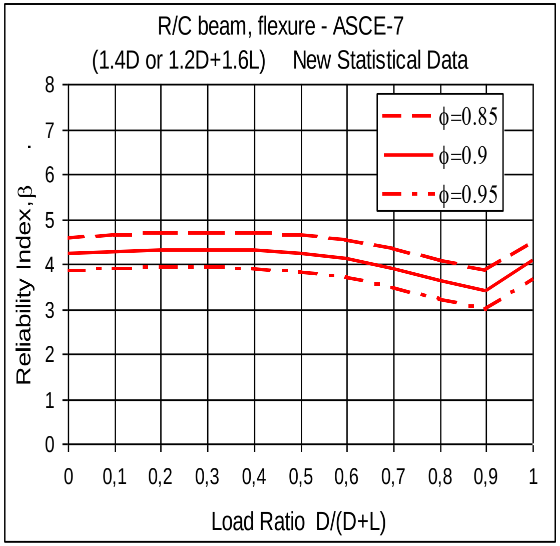
Examples of the Reliability Analysis

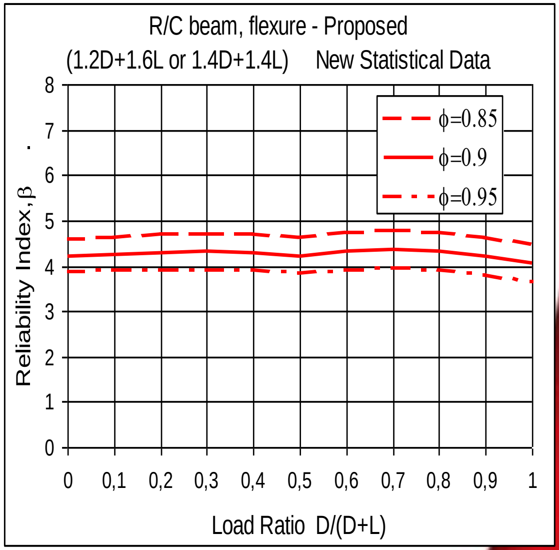
ACI 318-99
Old Statistical Data

ACI 318-05
New Statistical Data

ACI 318-05 with new load factor, 1.4(D+L)







Conclusions for ACI 318 Calibration

- Quality of materials (concrete and reinforcing steel) have improved in the last 20-30 years
- Reliability of structures designed according to “old” ACI 318 is now higher than the minimum acceptable level
- Resistance factors can be increased by 10-15%. Therefore, for the new load factors (ASCE 7), “old” resistance factors are acceptable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Thank you