# Reliability Considerations for Steel Frames Designed with Advanced Analysis

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# Features of Advanced Analysis

- Non-Linear Structural Analysis
  - e.g. Inelastic materials, P-Δ effects
- System Behavior
  - e.g. Frame stability
- Advantages over Existing Code
  - Individual Member Checking Not Required
  - Adjustment Factors Not Required
    - e.g. Effective length, Second-order effects, Interaction equations

# Reliability & Advanced Analysis

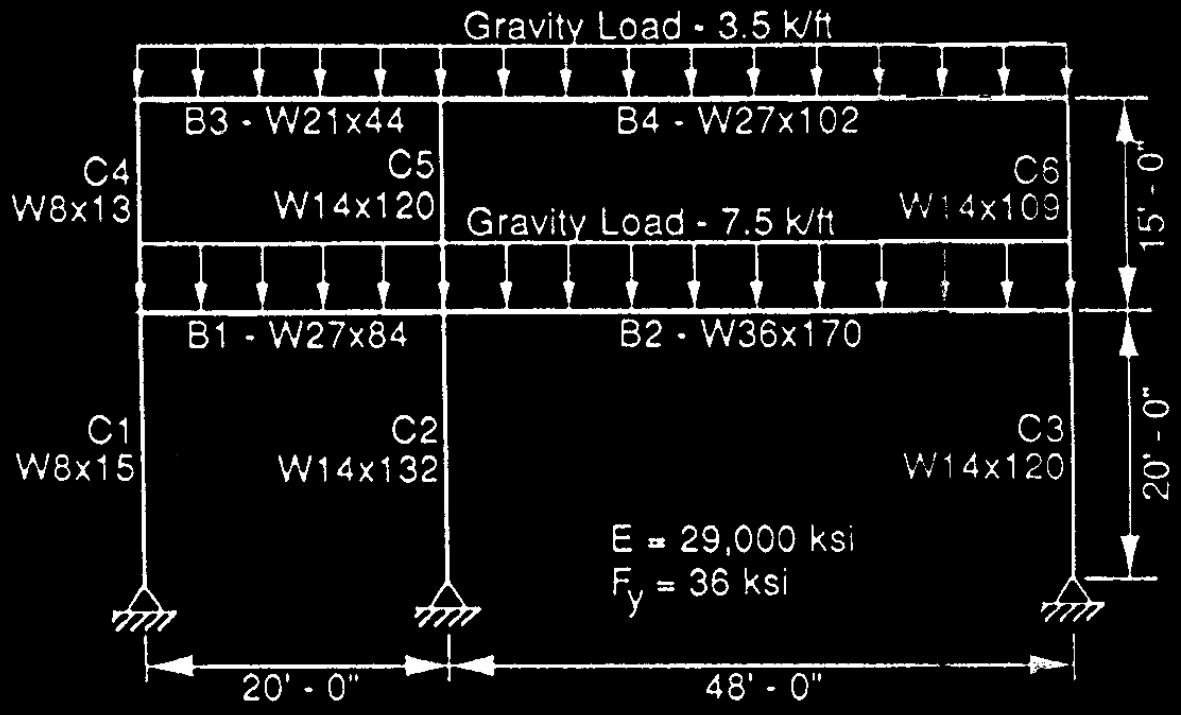
- Compare Reliability of Steel Frames
  Designed by LRFD vs. AA

- Compare Member (LRFD) vs. System (AA)
  Limit States

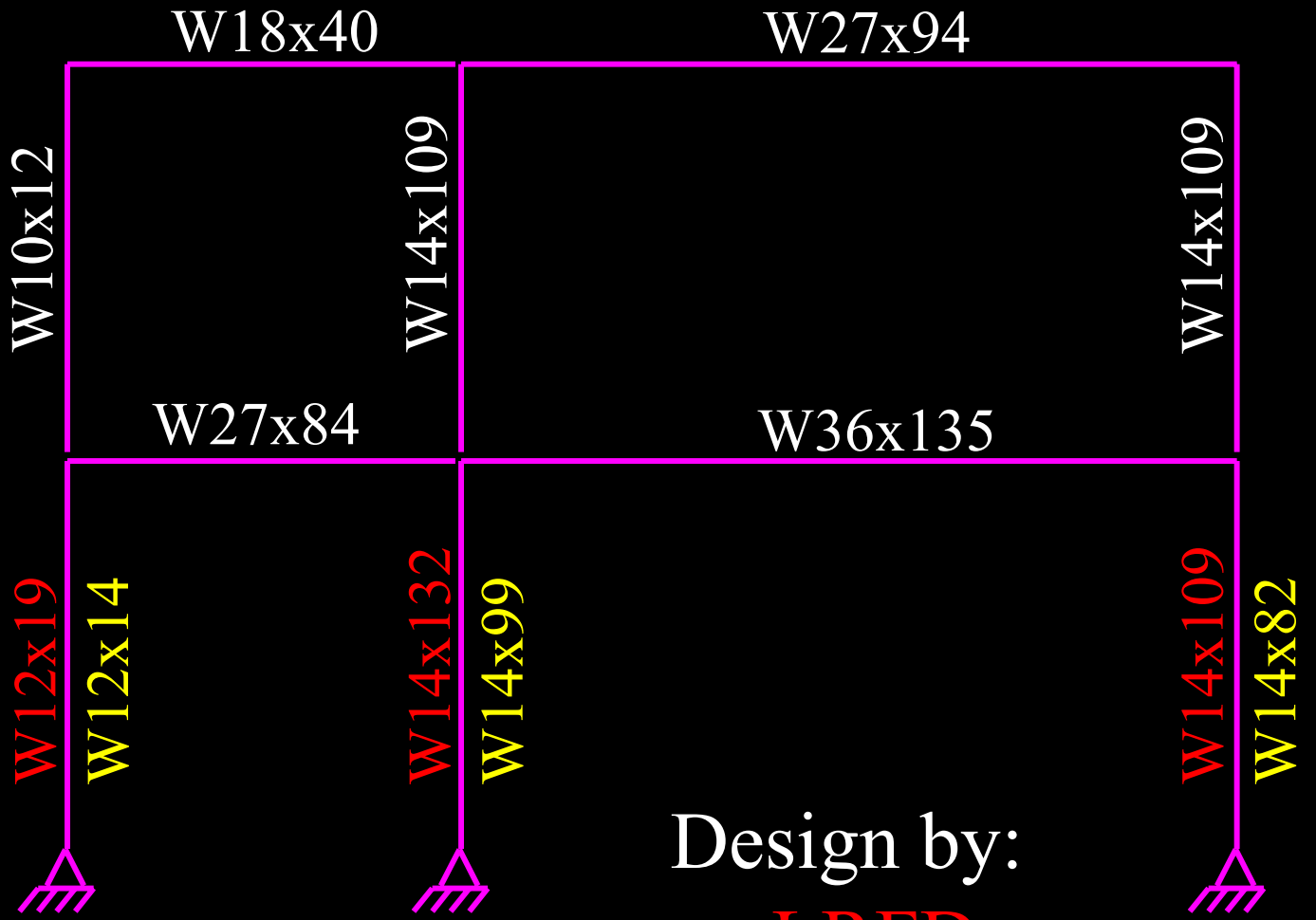
- Calculate Resistance Factors for AA

# Frames for Study

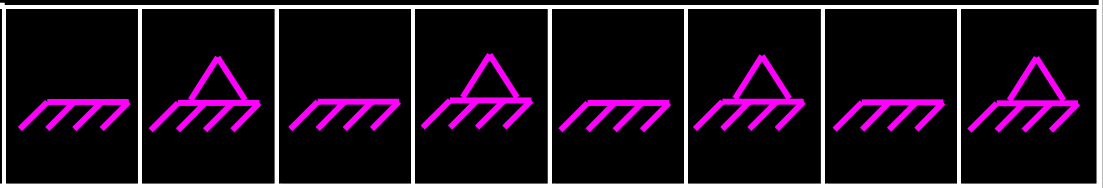
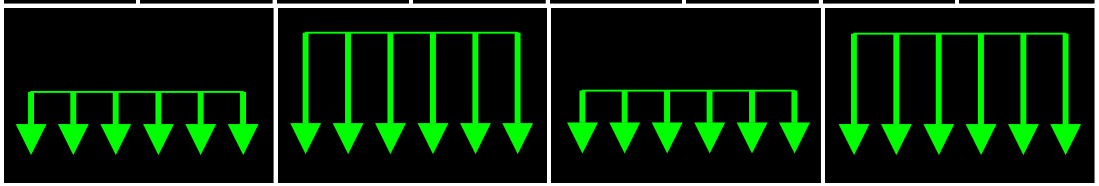
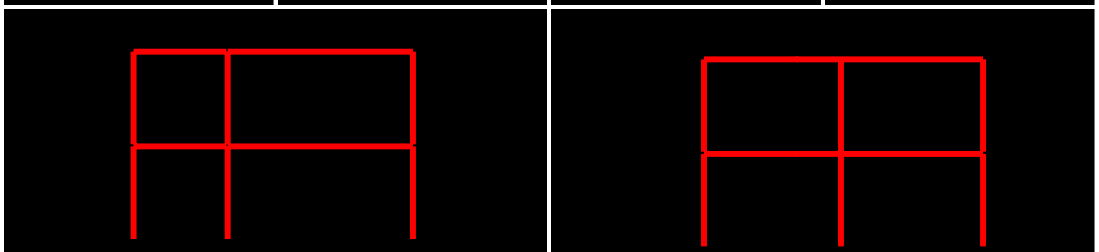
- Steel Frames from Ziemian et al. (1992)
- Designed by both LRFD (1986) and AA
- AA Design saves ~12% by weight



# Member Size Comparison



# Frames for Study

| | |
|---|---|
| 1. Member Sizes: | LRFD or AA |
| 2. Yield Strength: | Uncorrelated and Correlated |
| 3. Base Fixity |  |
| 4. Gravity Load |  |
| 5. Geometry |  |

Total = 32 Frames Analyzed

# Frame Analysis Details

- OpenSees (http://opensees.berkeley.edu)
  - Geometric Non-Linear
  - Fiber-Element Cross-Section
  - Elastic-Plastic Material
  - Out-of-Plumb Column Imperfection of $H/400$
  - Out-of-Plane Behavior Restrained
  - No Residual Stresses
- Random Yield Strength and Gravity Loads

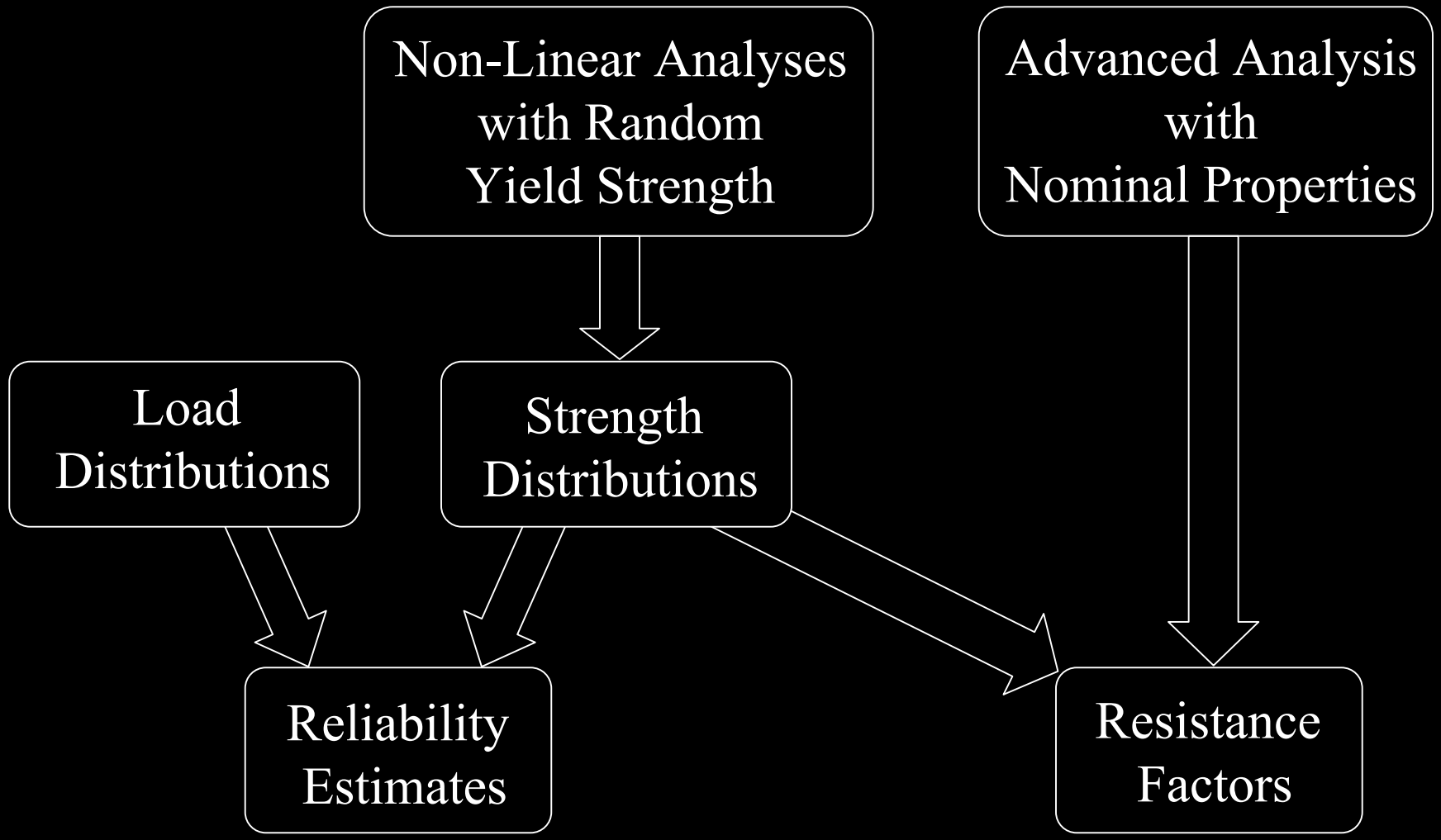
# Random Properties

- Yield Strength
  - 50 ksi Nominal
  - Normal Distribution with COV=0.10
  - Members Uncorrelated and Correlated
- Gravity Loads
  - Dead Load ~ Normal Distribution
  - Live Load ~ Extreme Type I Distribution
  - Both COV=0.10
- Consistent with LRFD Assumptions

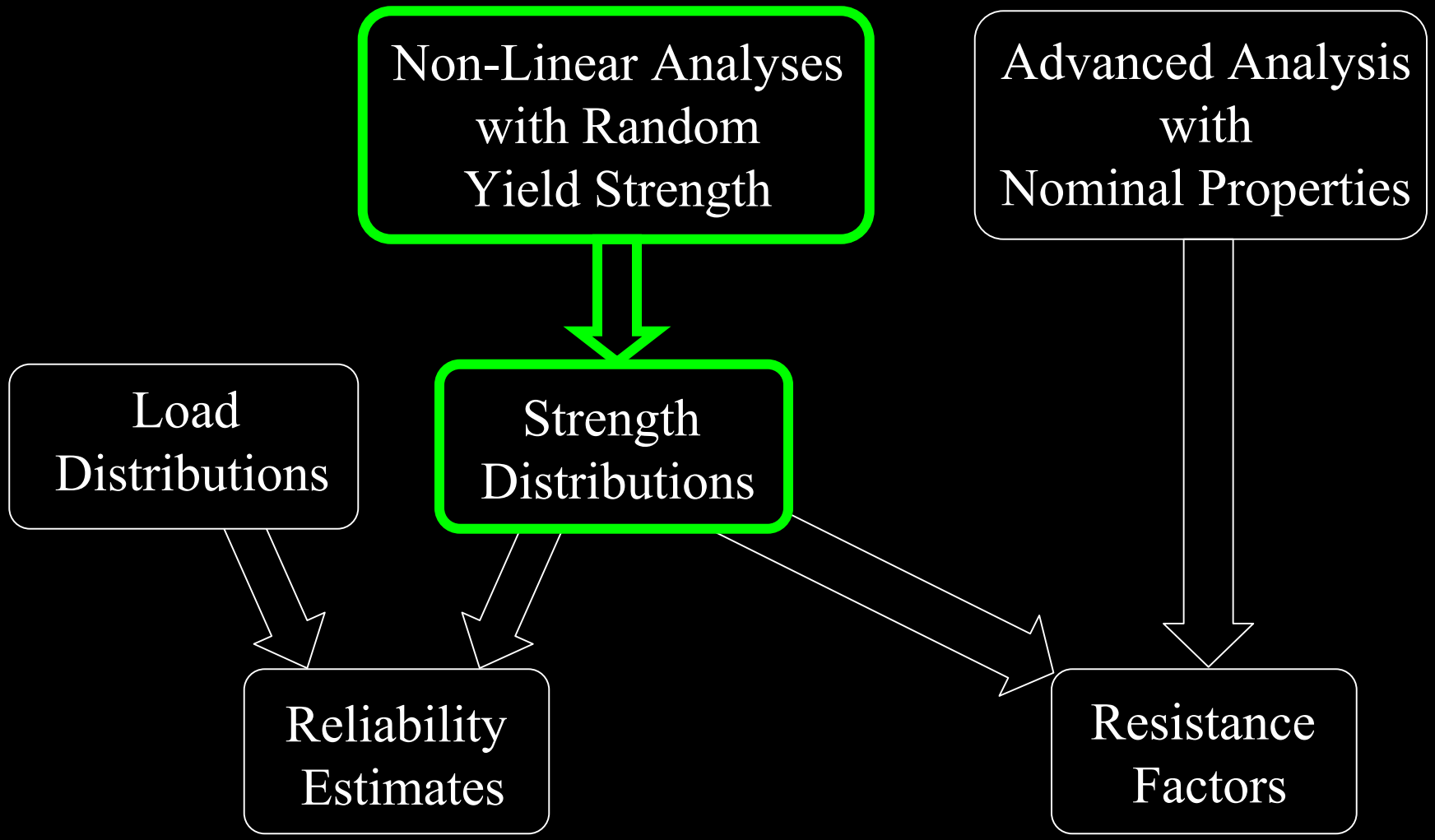
# Frame Simulation Details

- Each Frame of 32
  - 10,000 Samples with Random $F_y$
- Each Sample
  - Load Increased Until Failure
  - Strength Limit States considered
    - 1st Plastic Hinge
    - Plastic Collapse

# Overview


Non-Linear Analyses with Random Yield Strength
Advanced Analysis with Nominal Properties
Load Distributions
Strength Distributions
Reliability Estimates
Resistance Factors

# Overview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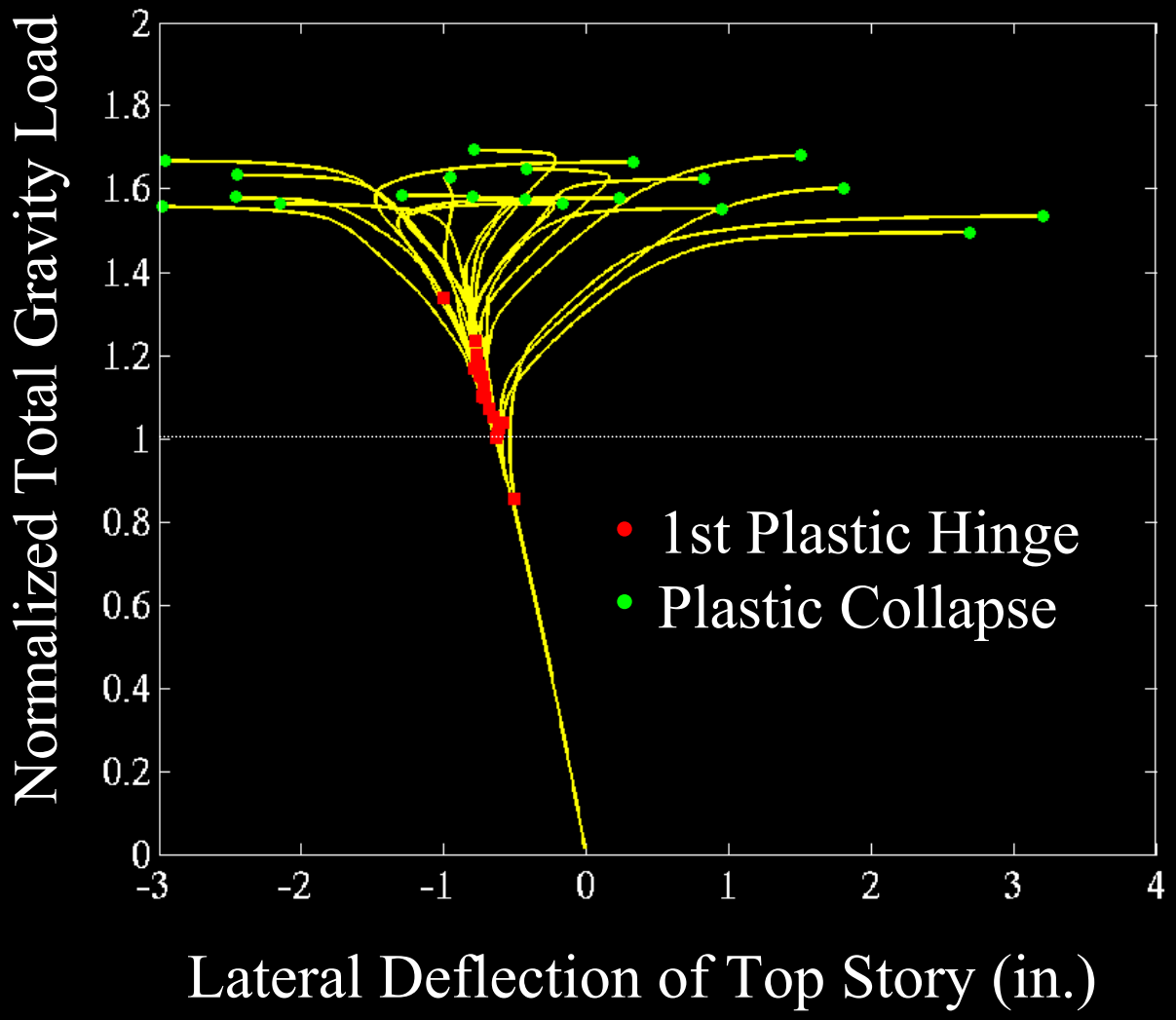
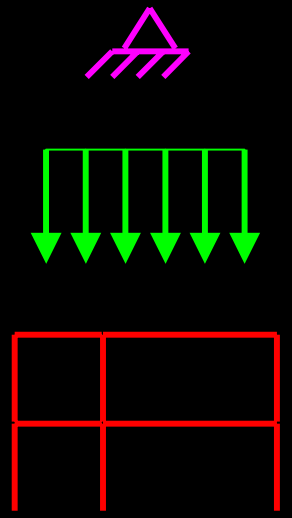
# Load-Deflection Behavior




Uncorrelated $F_y$
AA Design



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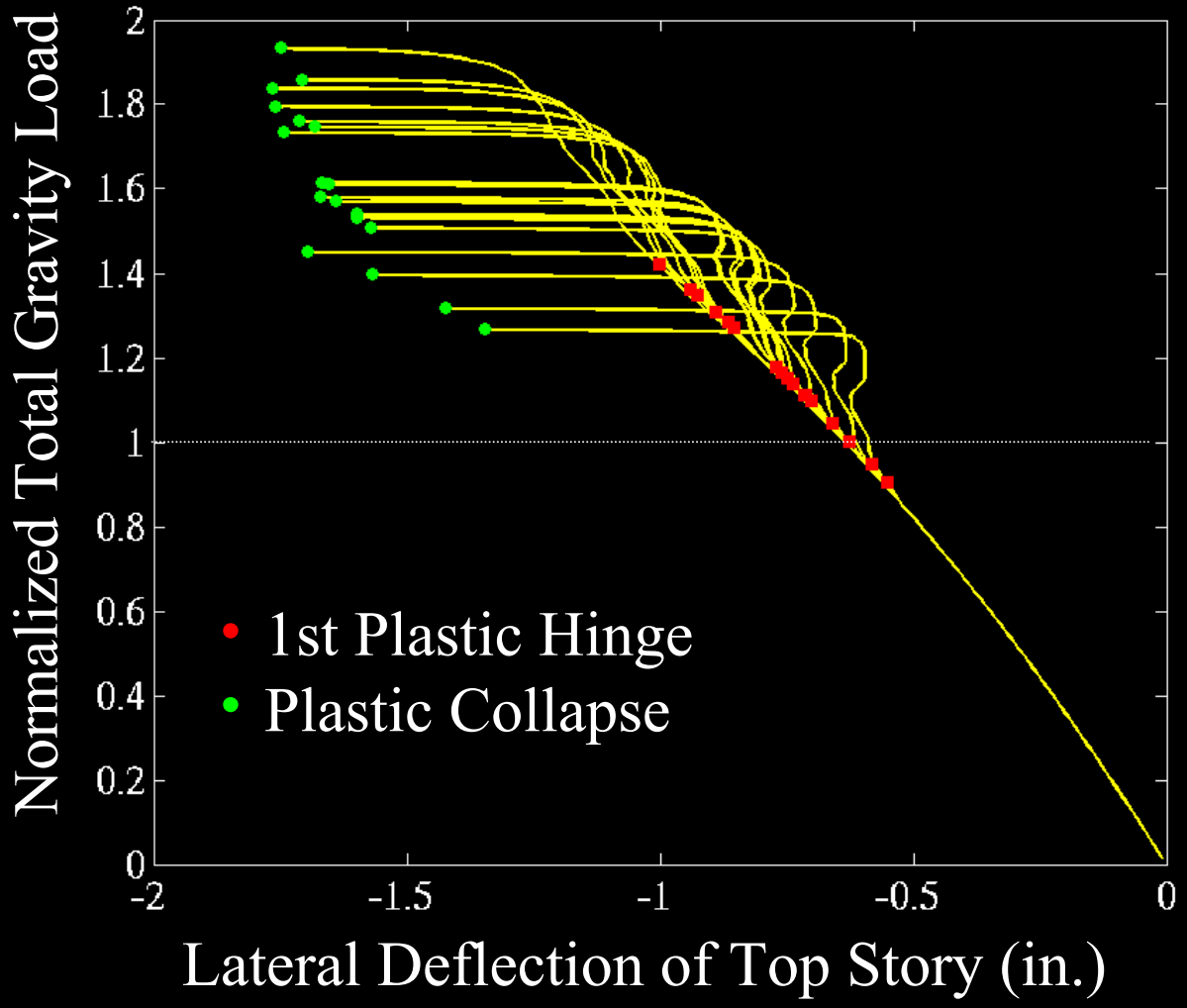
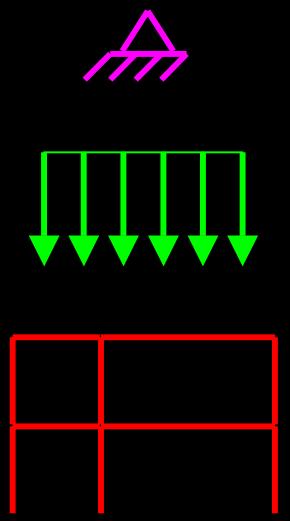
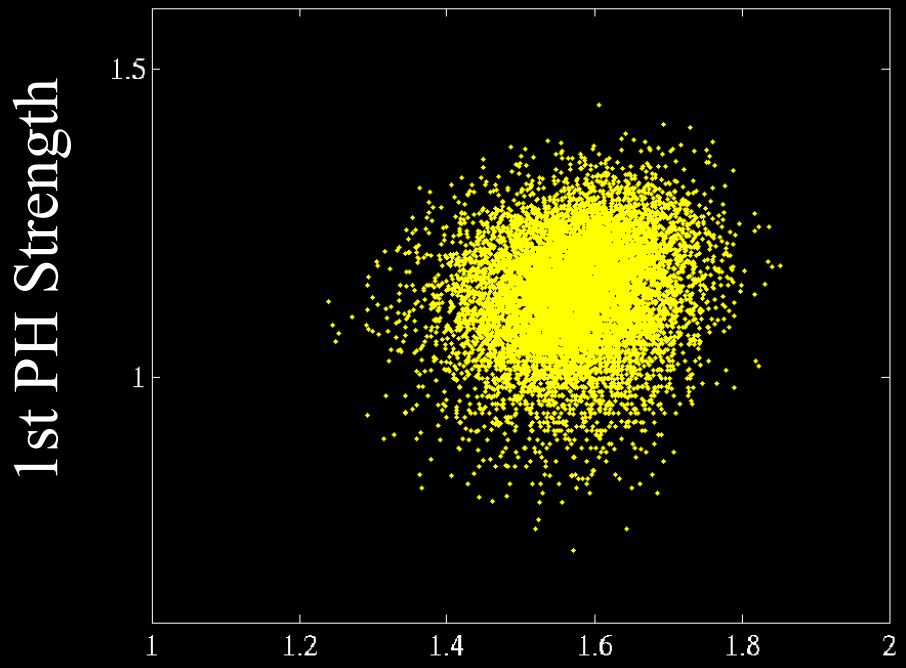
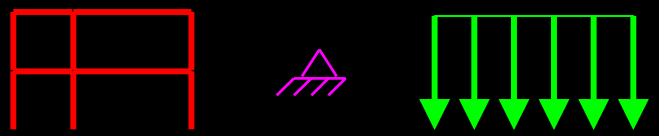



Correlated $F_y$
AA Design



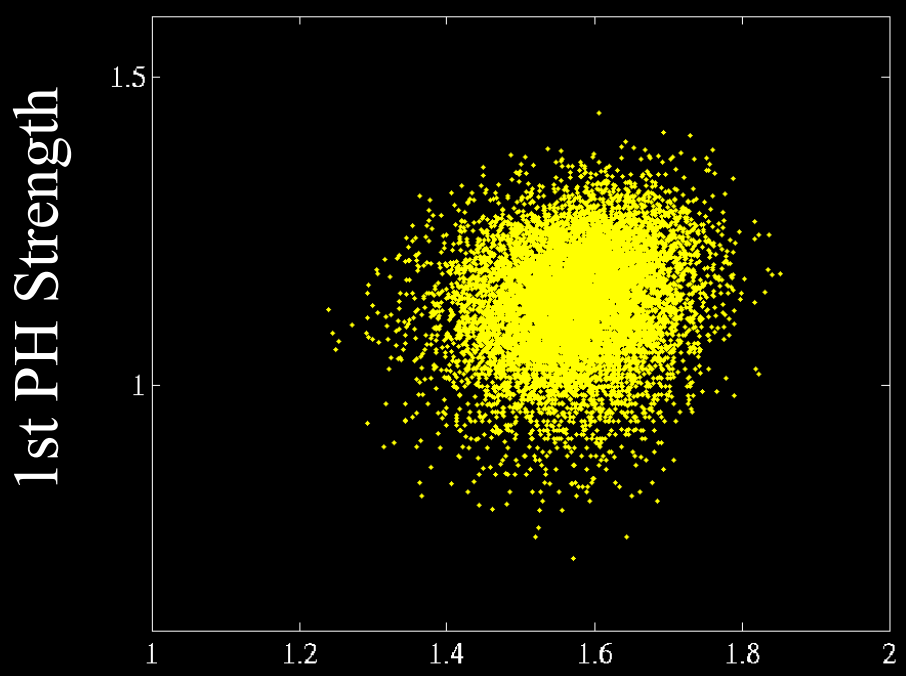
# Member vs. System Limit State

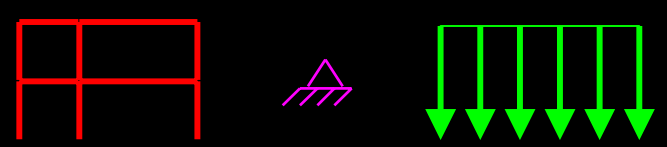


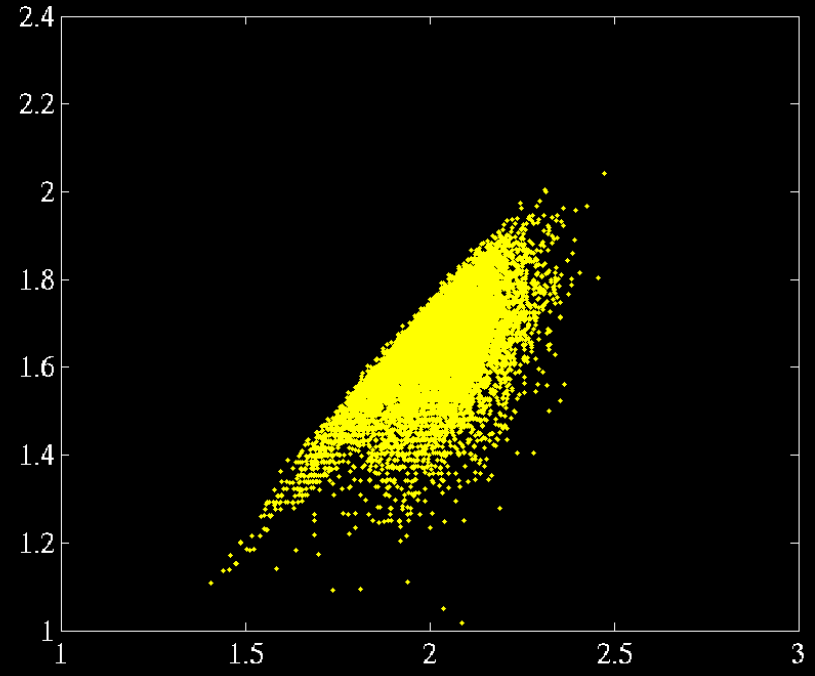
Uncorrelated $F_y$
AA Design

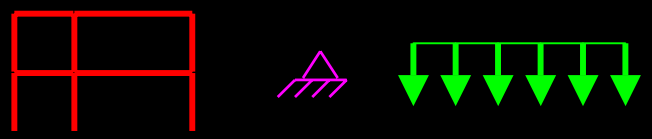
# Member vs. System Limit State



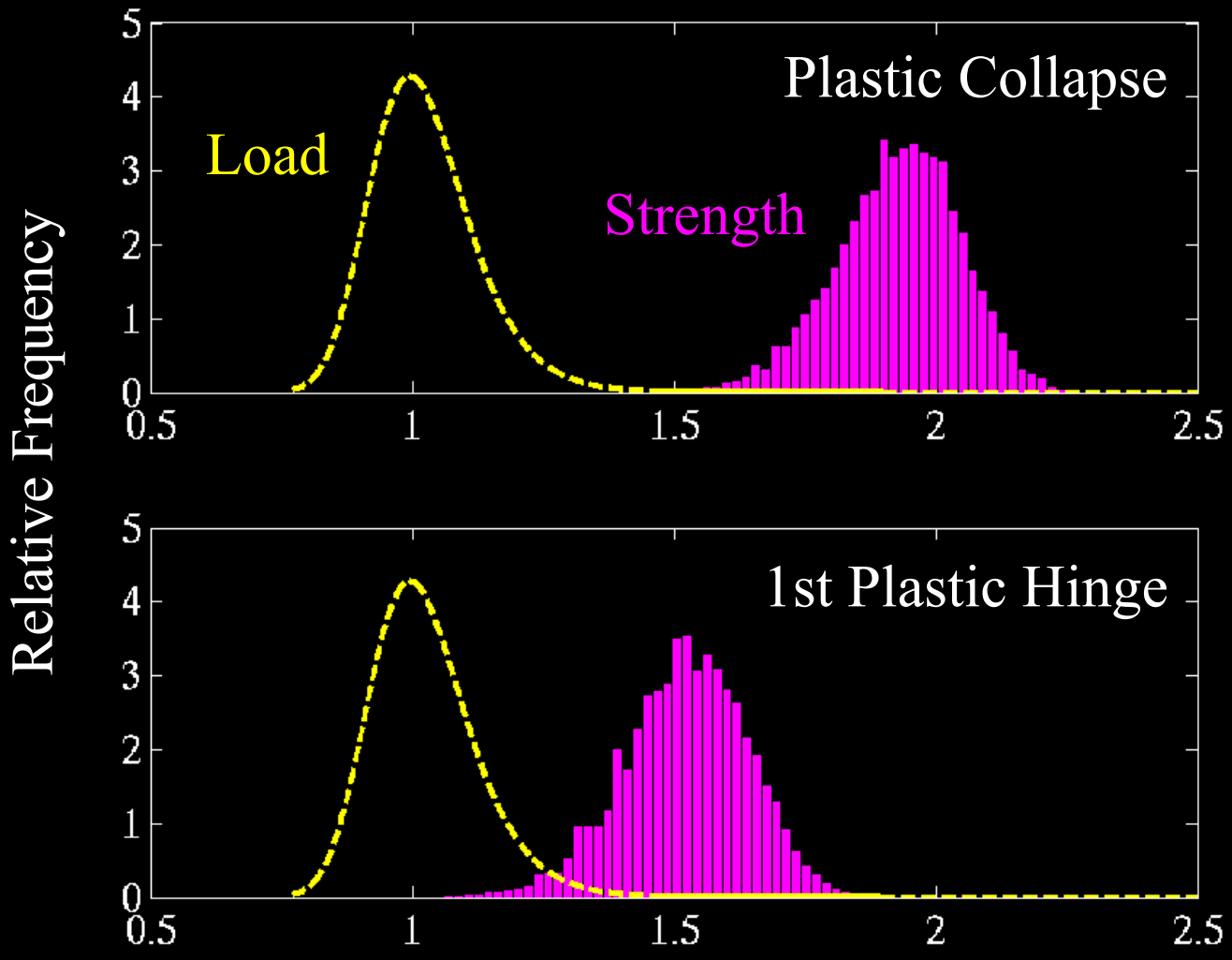
Uncorrelated $F_y$
AA Design



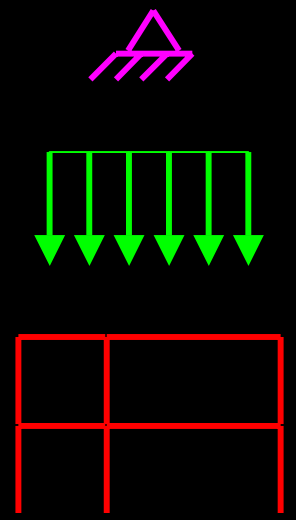



Uncorrelated $F_y$
LRFD Design

# Strength Distributions

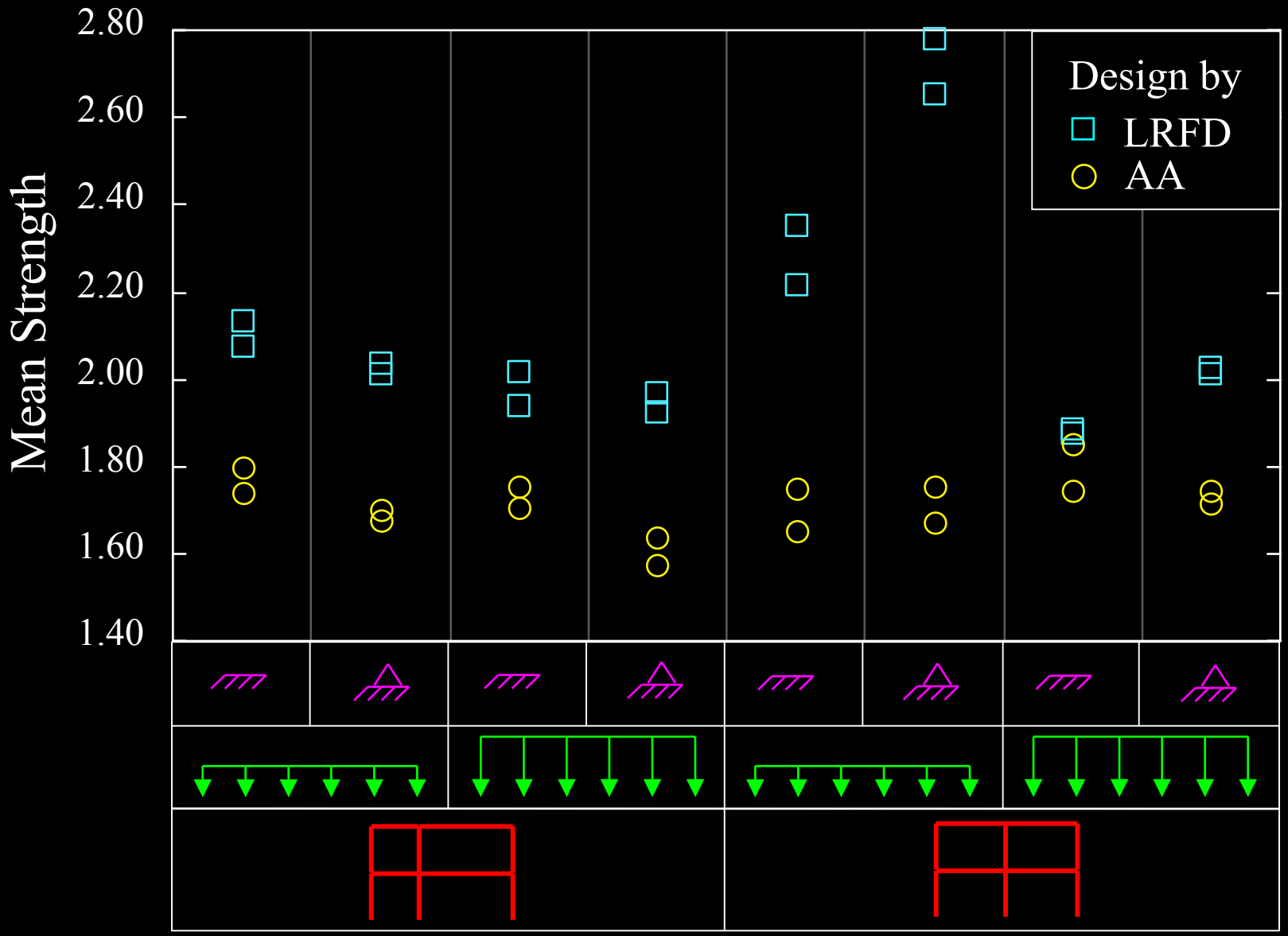



Uncorrelated $F_y$
LRFD Design

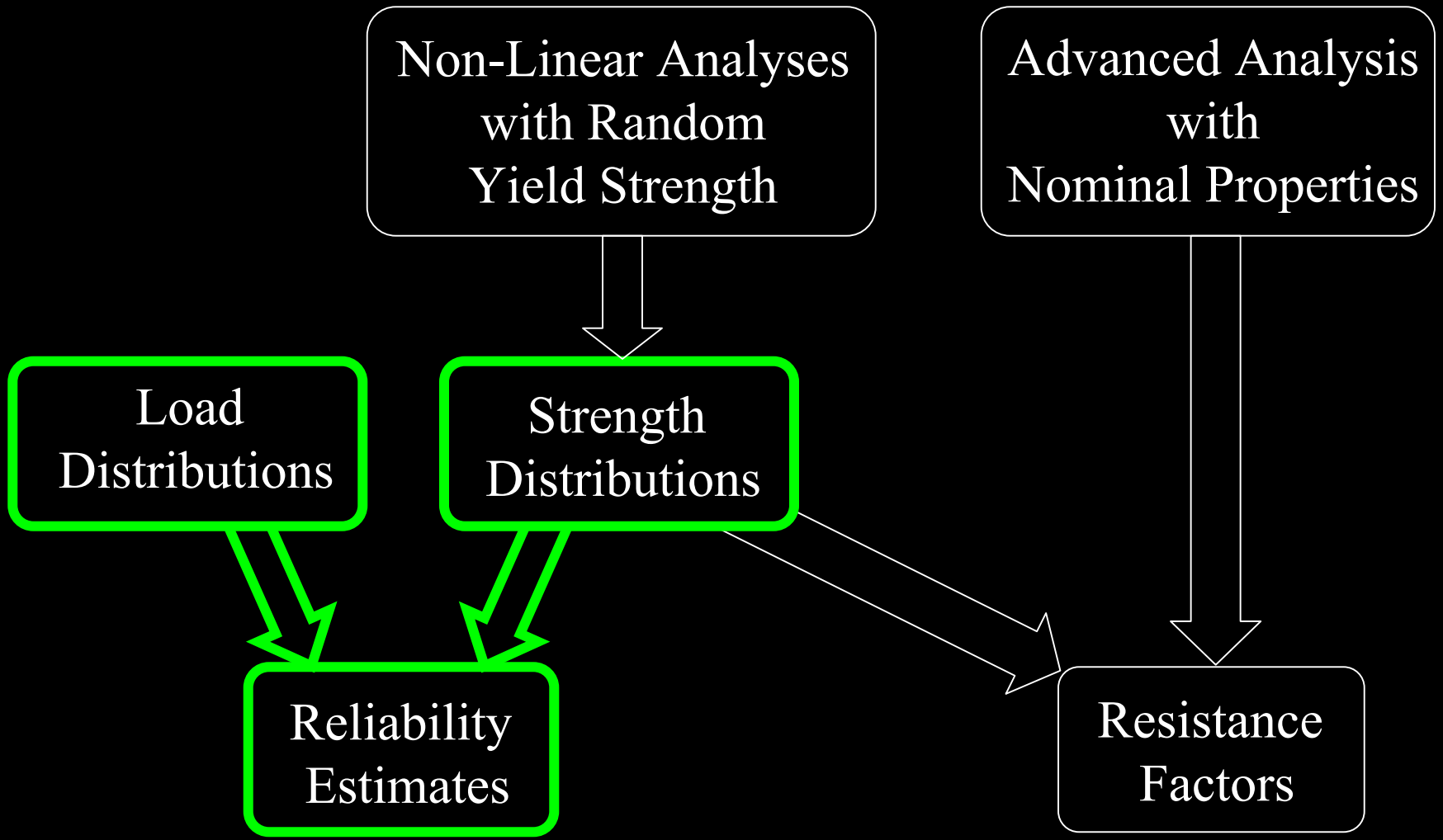


10,000 samples

# Mean Strength at Plastic Collapse



# Overview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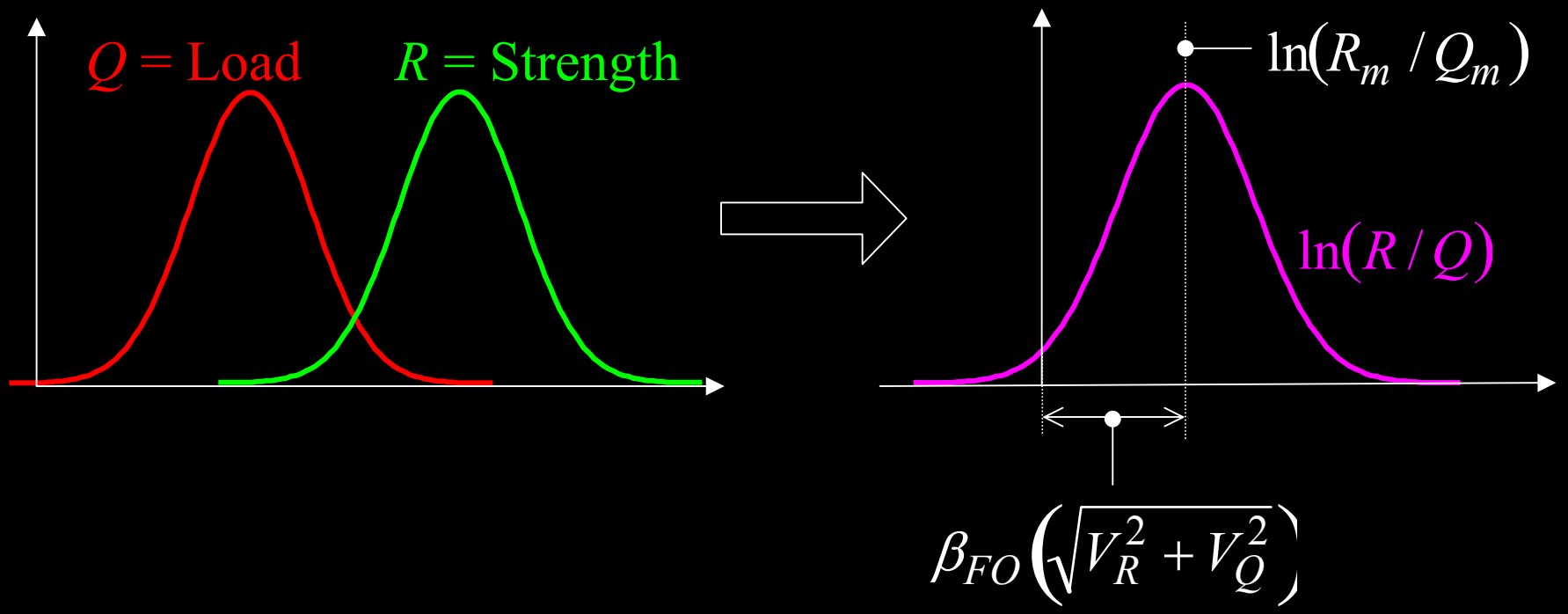
# Reliability and LRFD



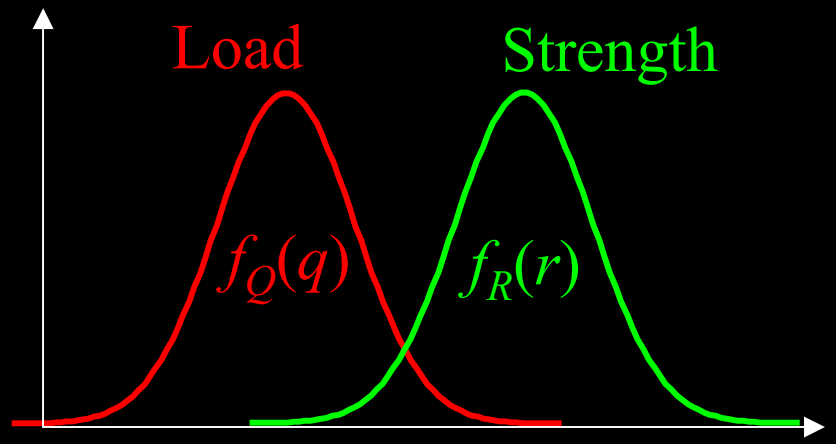

First-Order Reliability $\beta_{FO} = \dfrac{\ln(R_m / Q_m)}{\sqrt{V_R^2 + V_Q^2}}$

# Reliability by Sampling

## Probability of Failure

$$P_f = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(r,q) f_R(r) f_Q(q)\, dr\, dq$$

$$I(r,q)\begin{cases} = 1 \text{ for } R \le Q \\ = 0 \text{ for } R > Q \end{cases}$$




## Monte Carlo Estimate

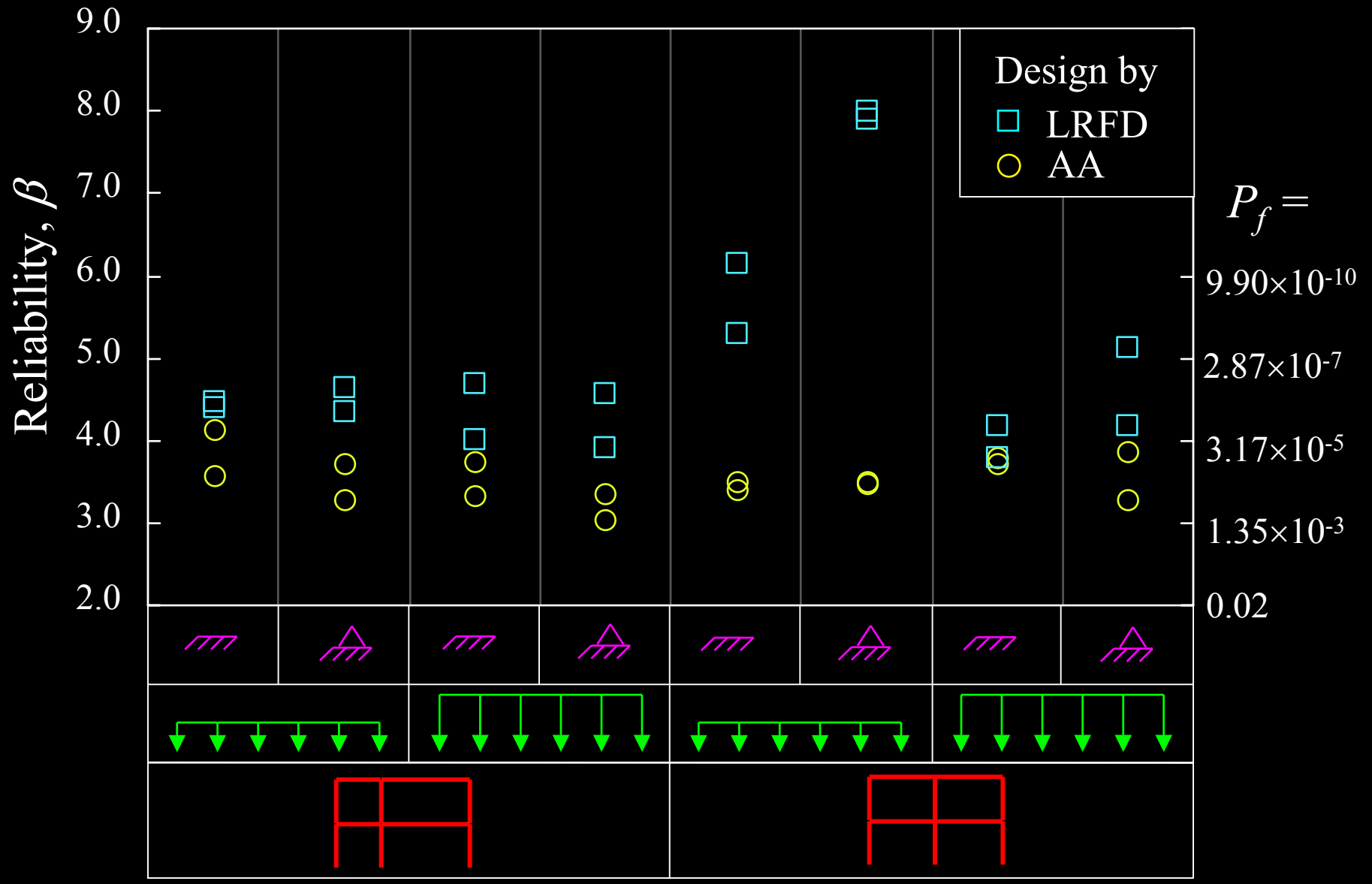
$$\hat{P}_f = \frac{1}{N}\sum_{i=1}^{N} I(r_i, q_i)$$

$r_i$ sampled from $f_R$

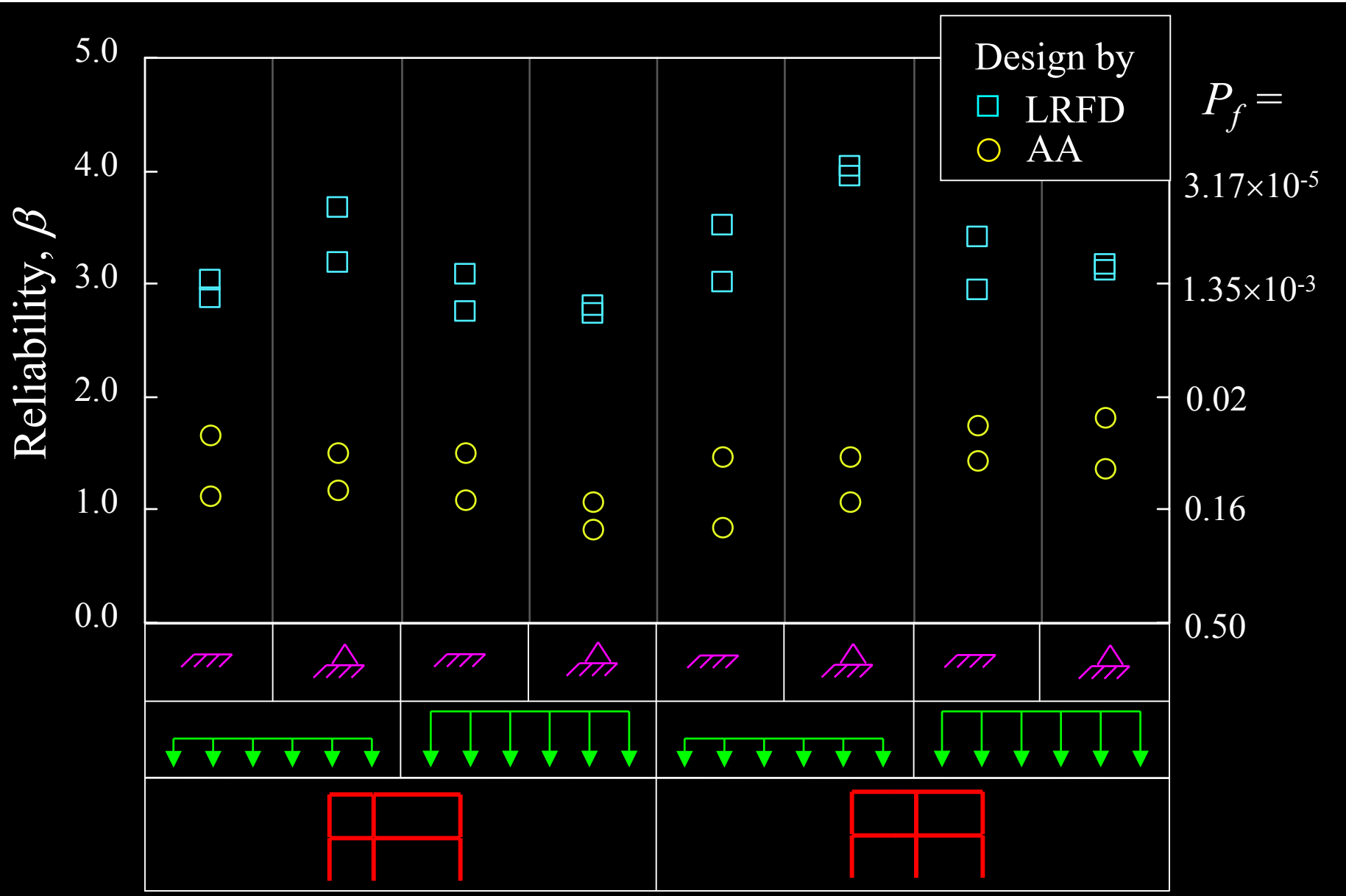
$q_i$ sampled from $f_Q$

## Reliability $\beta = -\Phi^{-1}\left(\hat{P}_f\right)$

# Reliability at Plastic Collapse



# Reliability at 1st Plastic Hinge



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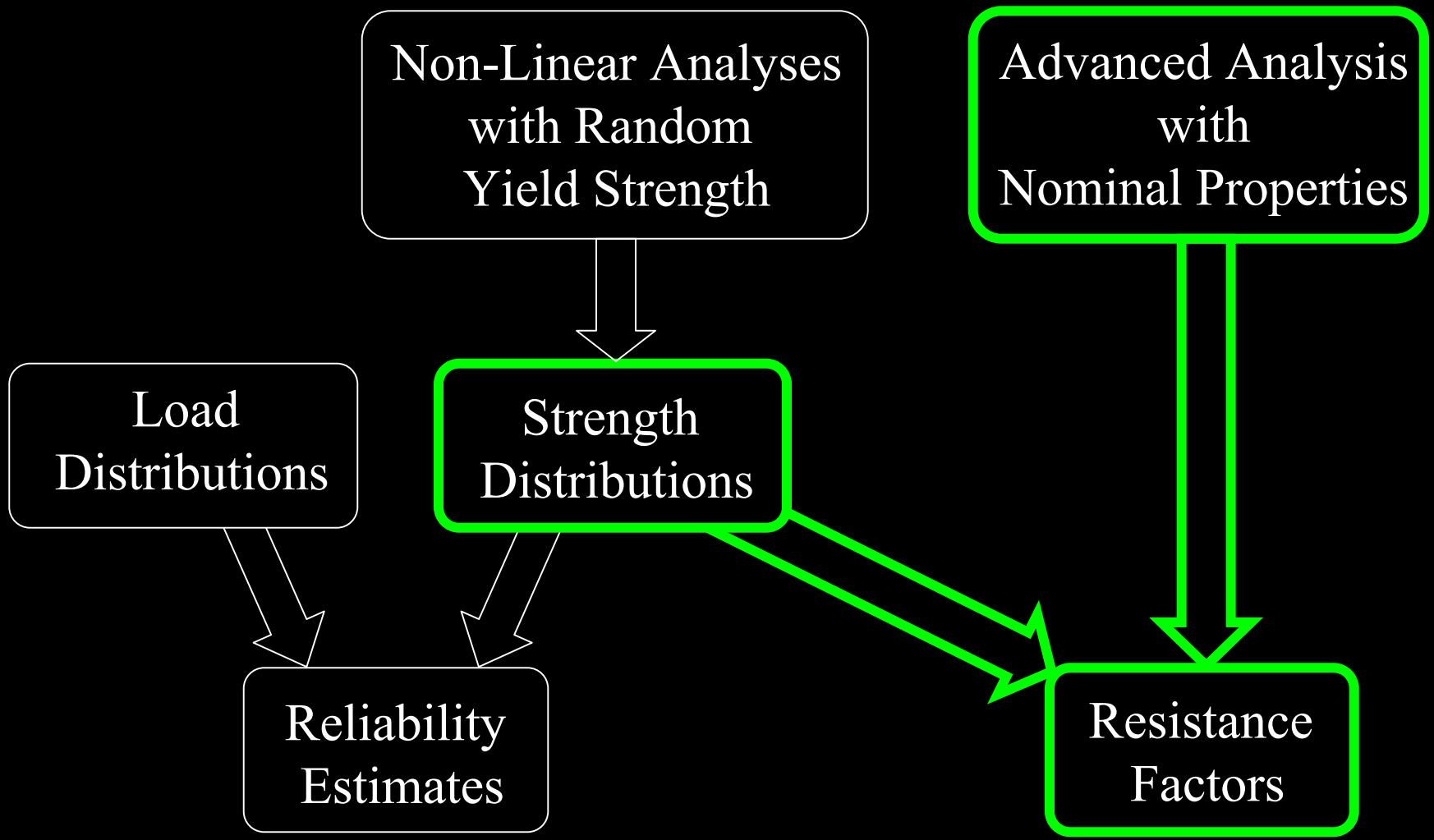
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# Resistance Factors

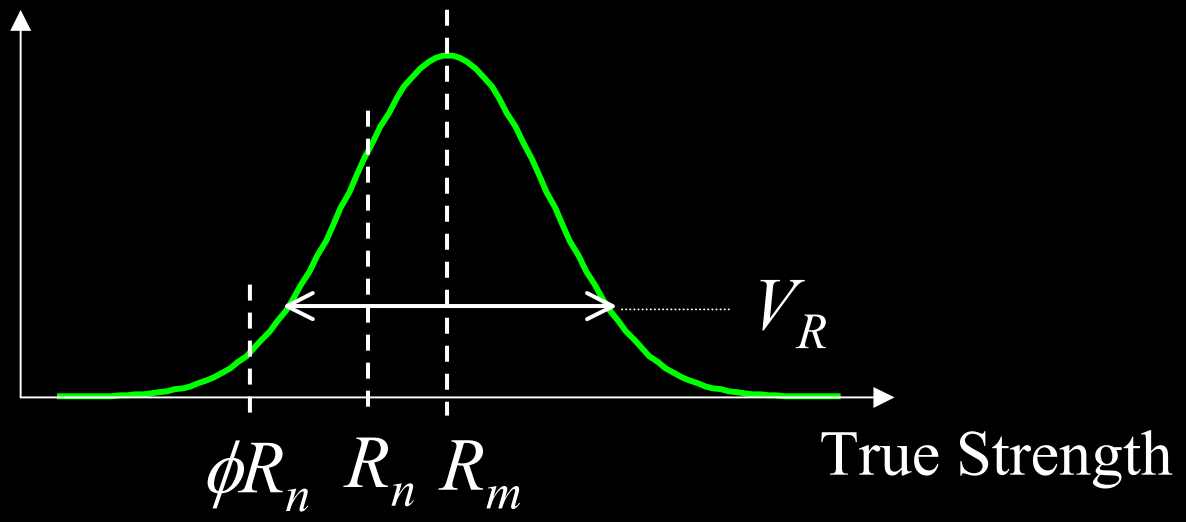
$$\phi = (R_m / R_n)\exp(-0.55\beta_t V_R)$$

Mean of "True" Strength

Nominal Strength

Target Reliability

Variation of "True" Strength



# Resistance Factors of LRFD

$$\phi = (R_m / R_n)\exp(-0.55\beta_t V_R)$$

$$R_m / R_n = \underbrace{P_m M_m F_m}_{\text{Means}} = 1.07 \qquad V_R = \sqrt{\underbrace{V_P^2 + V_M^2 + V_F^2}_{\text{COVs}}} = 0.15$$

LRFD Bias Factors:

$P$ = Professional

$M$ = Material

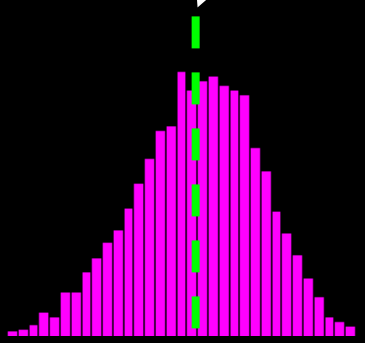
$F$ = Fabrication

# Resistance Factors for AA

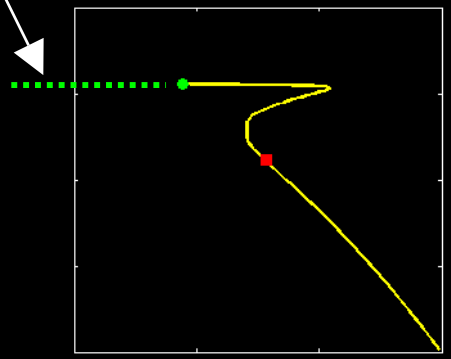
$$\phi = (R_m / R_n)\exp(-0.55\beta_t V_R)$$

$$R_m^{AA} / R_n^{AA} = B_m^{AA}$$

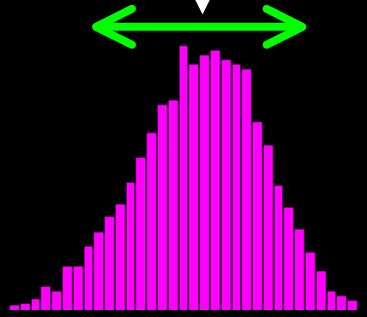
$$V_{B^{AA}} = \sqrt{V_{R^{AA}}^2 + V_F^2}$$



AA Strength Distribution

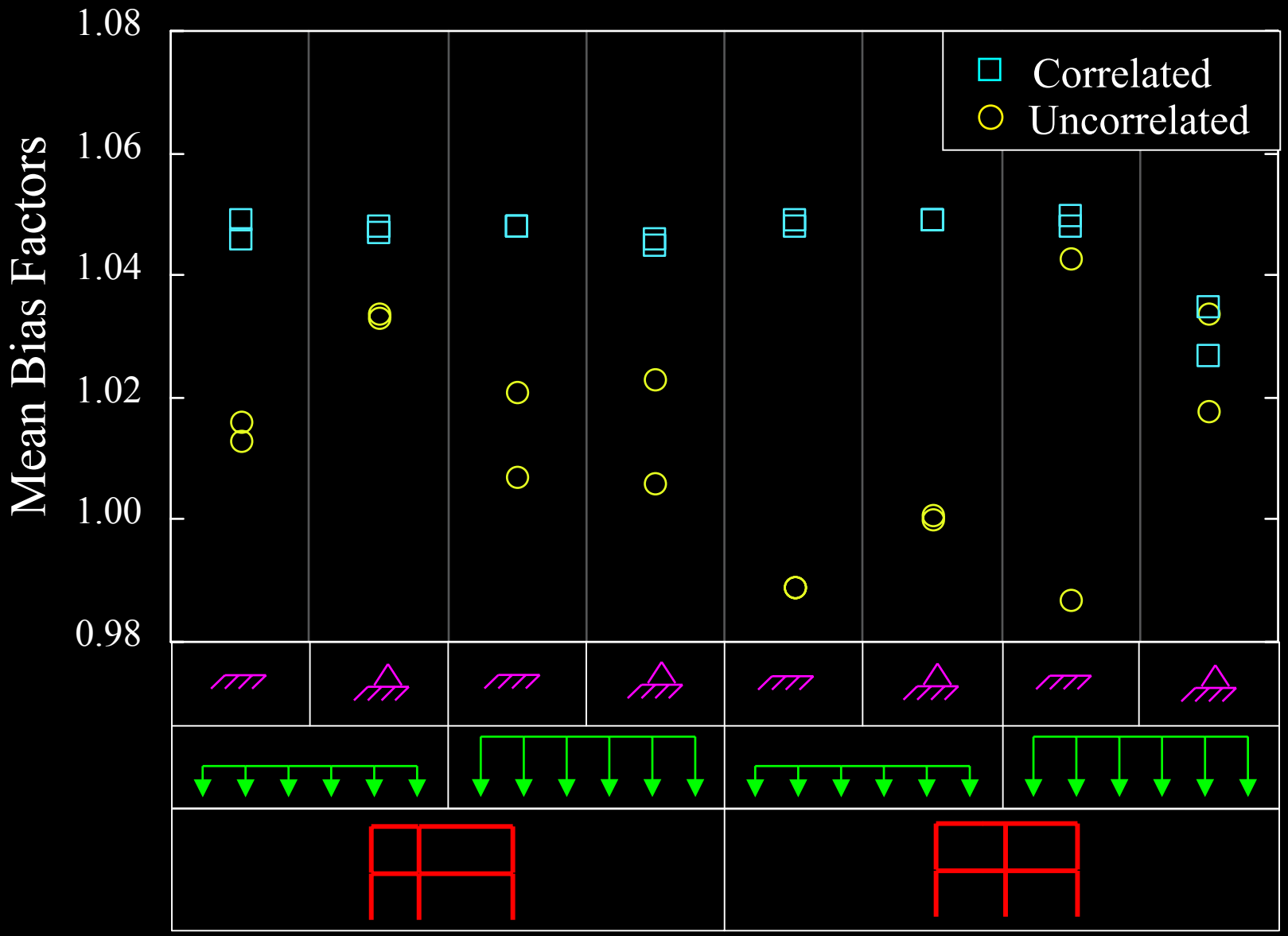


AA Nominal Strength

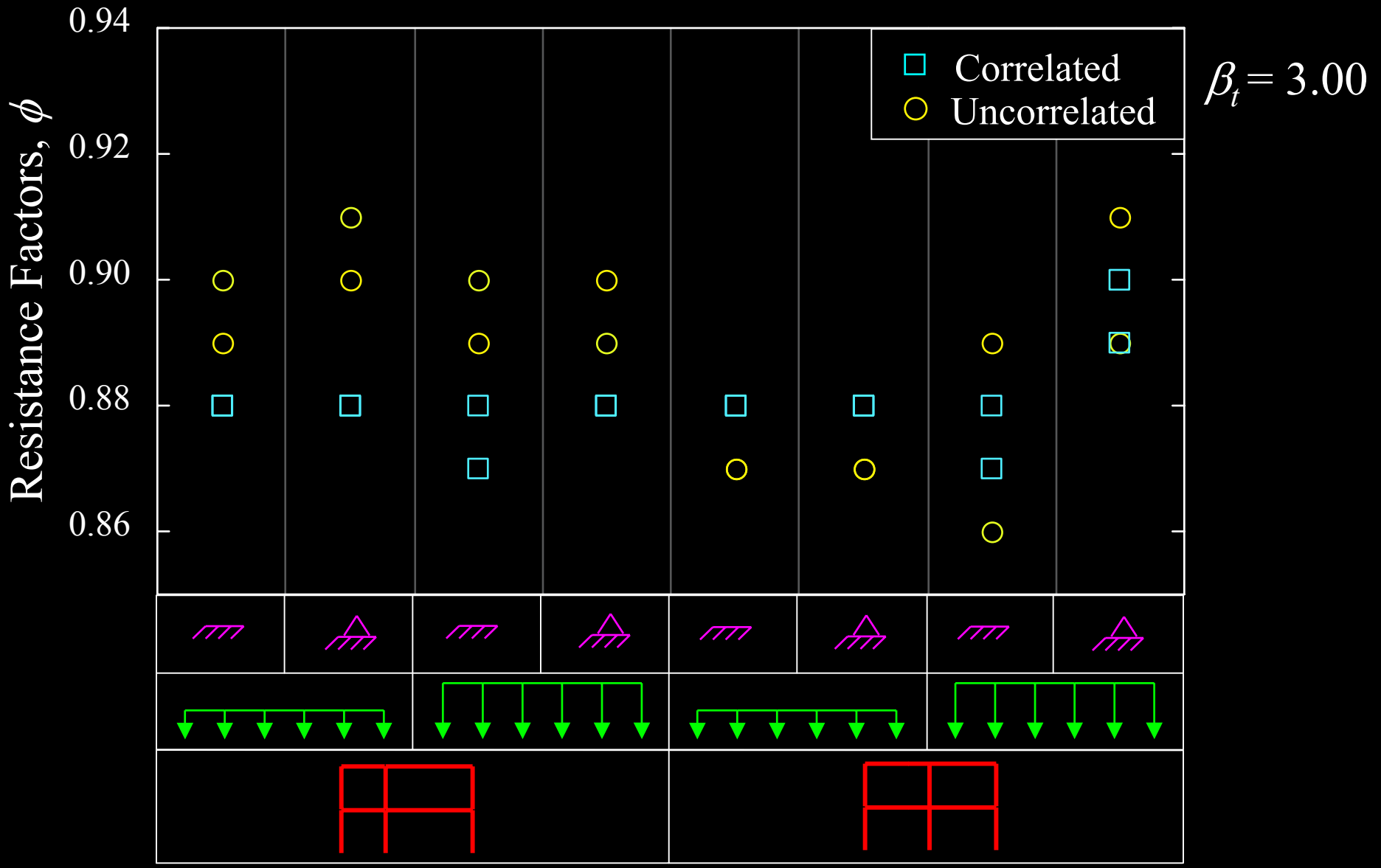


AA Strength Distribution

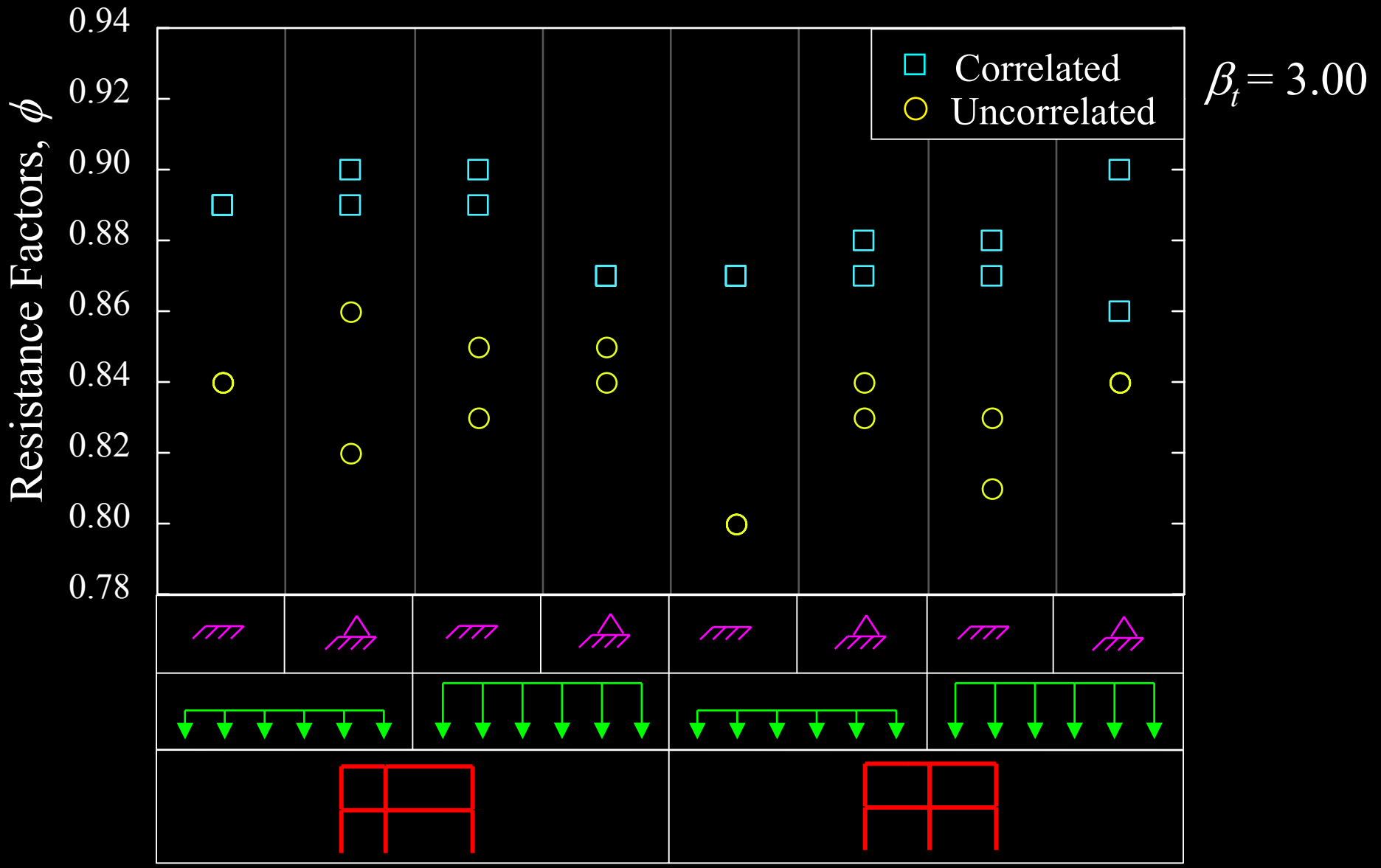
# Mean Bias Factors



# Resistance Factors for AA at PC



# Resistance Factors for AA at 1st PH



# Summary of Resistance Factors

| Limit State | Plastic Collapse | | 1st Plastic Hinge | |
|---|---|---|---|---|
| $F_y$ | Uncorr. | Corr. | Uncorr. | Corr. |
| Min | 0.86 | 0.87 | 0.80 | 0.86 |
| Mean | 0.89 | 0.88 | 0.83 | 0.88 |
| Max | 0.91 | 0.90 | 0.86 | 0.90 |

Target Reliability, $\beta_t = 3.00$

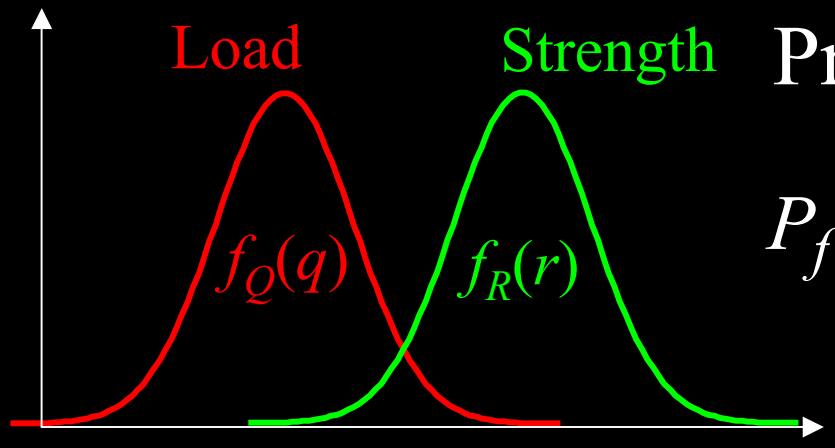
# Conclusions

- Probabilistic Basis for AA Resistance Factors
- No Simple Transformation from Member to System Design Approach
- Increased Probability of 1st PH with Design by AA

# Future Work

- Serviceability Concerns due to Increased Probability of 1st PH with AA
- Is a Single $\phi$ Appropriate for ALL Steel Frames?
- How to Apply $\phi$ in AA?
  - To System Strength
  - To Member Properties

# Reliability by Sampling




## Probability of Failure

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$$I(r,q)\begin{cases} = 1 \text{ for } R \le Q \\ = 0 \text{ for } R > Q \end{cases}$$

## Monte Carlo Estimate

$$\hat{P}_f = \frac{1}{N}\sum_{i=1}^{N} I(r_i, q_i)$$

$$\beta = -\Phi^{-1}\left(\hat{P}_f\right)$$

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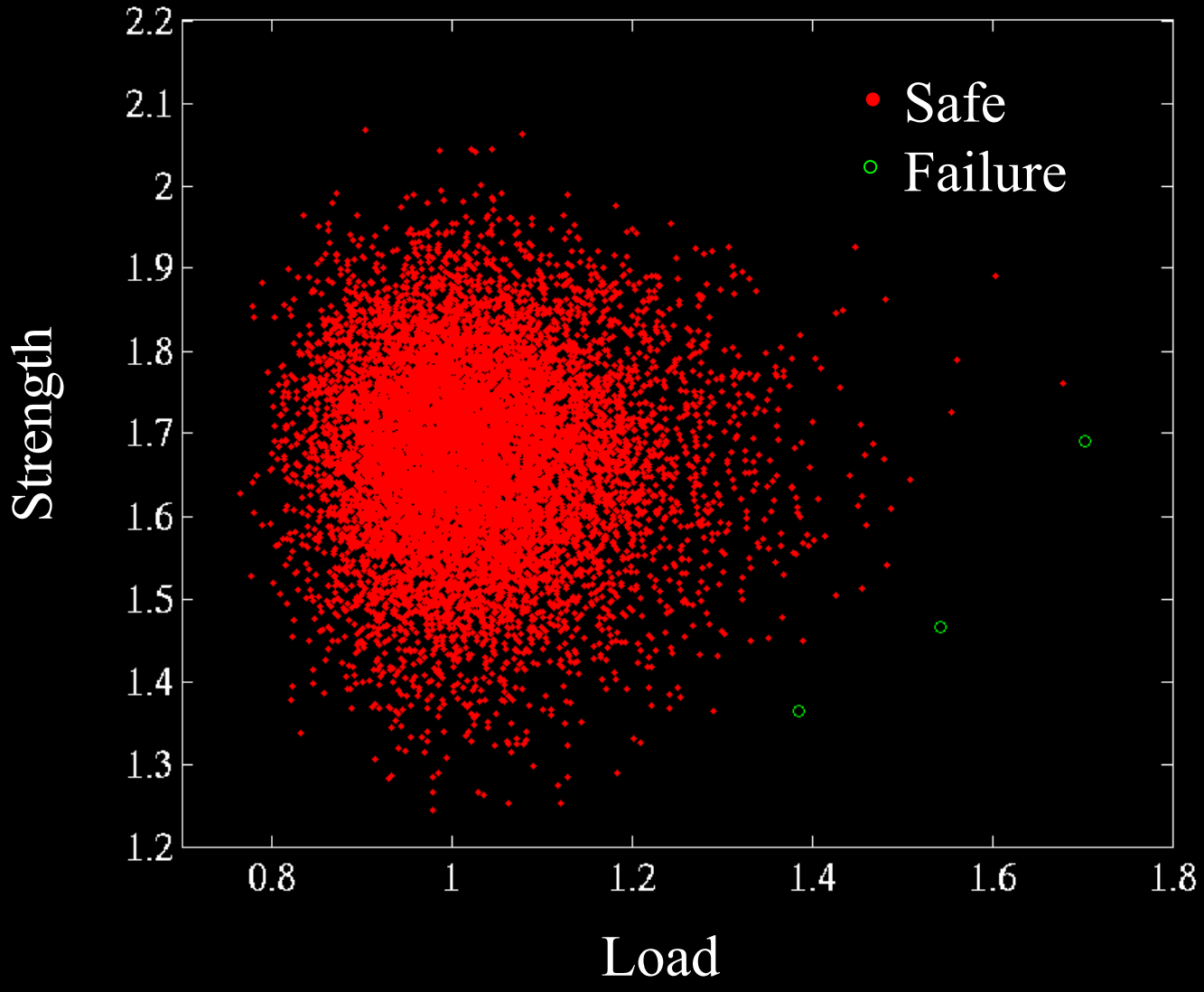
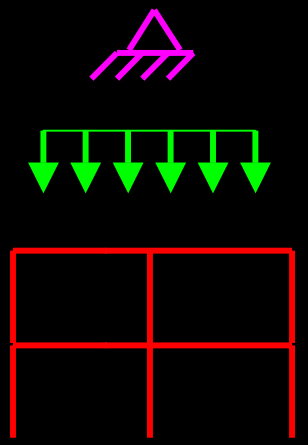



Uncorrelated $F_y$
AA Design



# Reliability by Sampling

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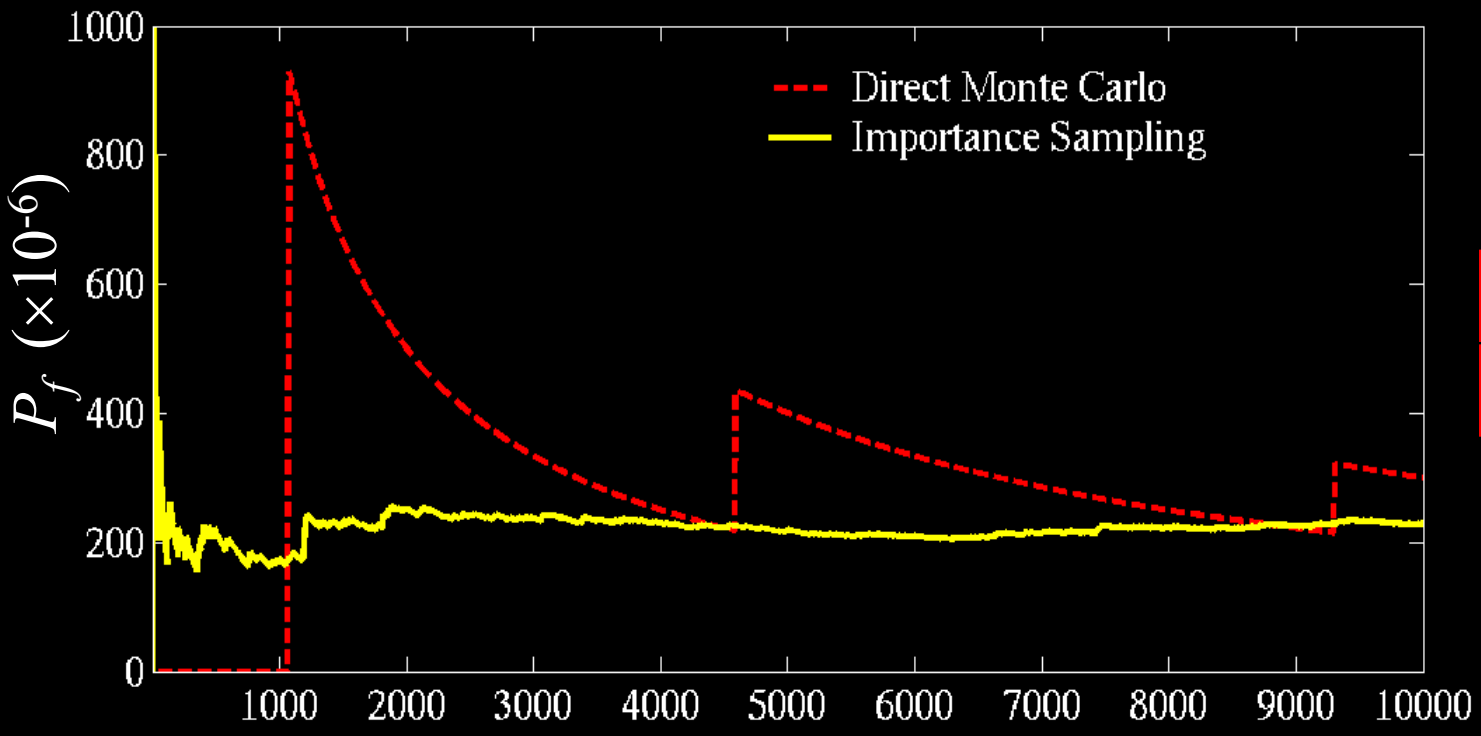


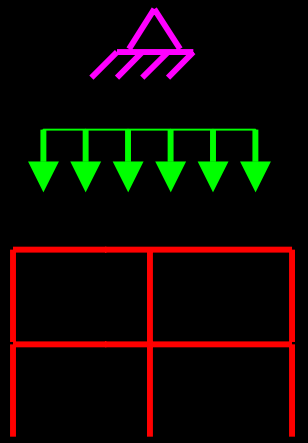

| | AA | LRFD |
|---|---|---|
| Uncorr. | ○ | □ |
| Corr. | ○ | □ |

| | |
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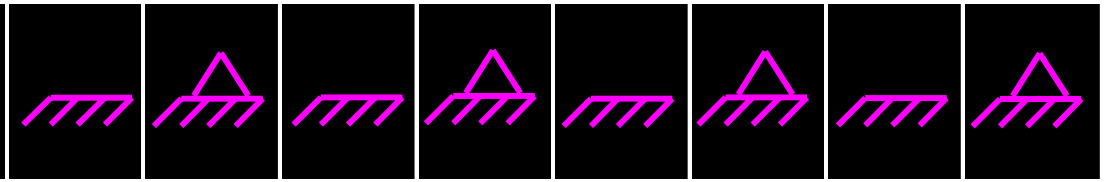
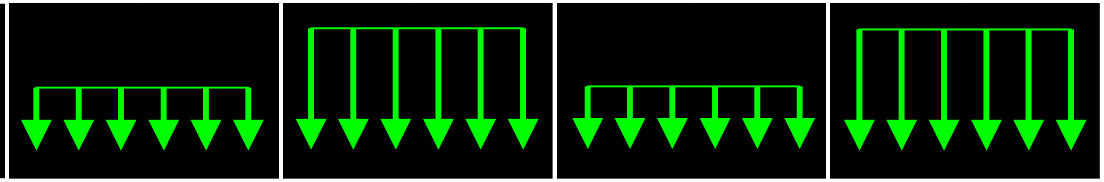
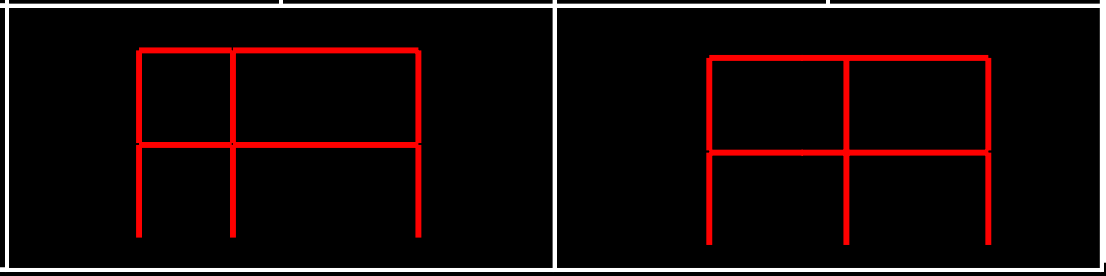
| 3. Base Fixity |  |
| 4. Gravity Load |  |
| 5. Geometry |  |

| Design: | AA | LRFD |
|---|---|---|
| Uncorr. | ○ | □ |
| Corr. | ○ | □ |

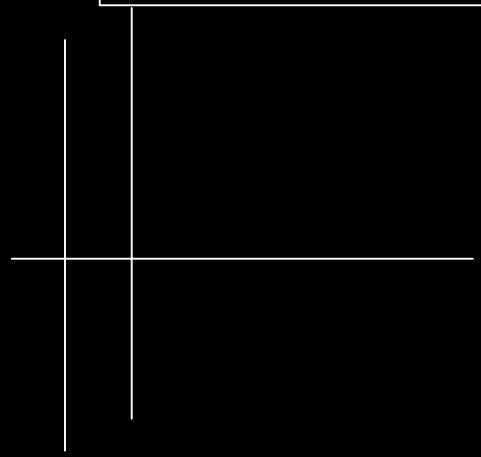
| | Design by | |
|---|---|---|
| | AA | LRFD |
| Uncorr. | ○ | □ |
| Corr. | ○ | □ |

Design by
□ LRFD
○ AA

□ First-Order
○ Monte Carlo

□ Correlated
○ Uncorrelated

Design by
□ LRFD
○ AA



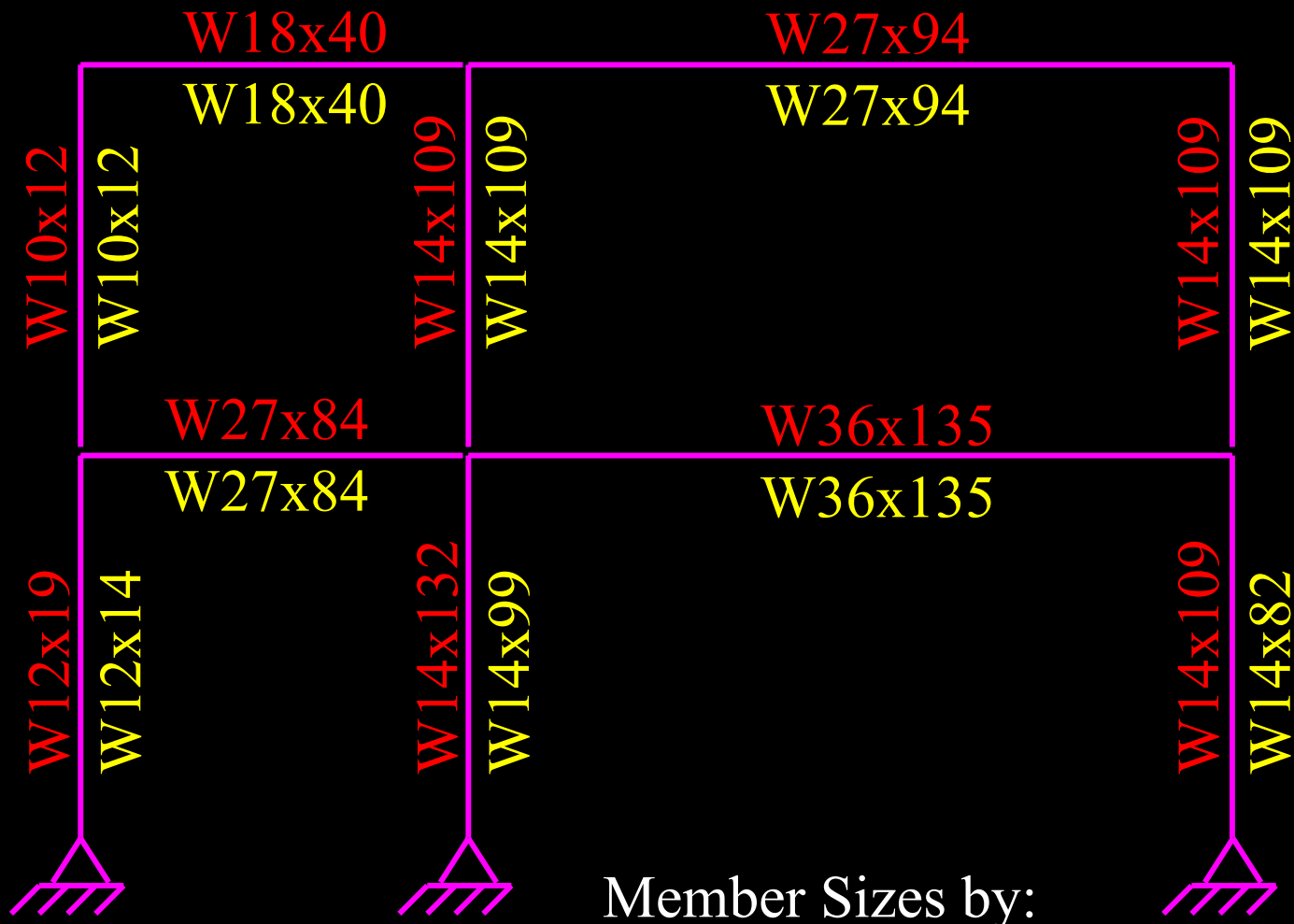
# Simulation Results

- Field of F-D curves
- Histograms of Strength, 1st PH
- Plots of mean, COV
- Estimates of Pf, beta
- Plots of Pf, beta
- Correlation of Strength, 1st PH

# Reliability and Advanced Analysis

- What Reliability is Associated with Design by AA?
- Implications for Resistance Factor, phi

# Member Size Comparison

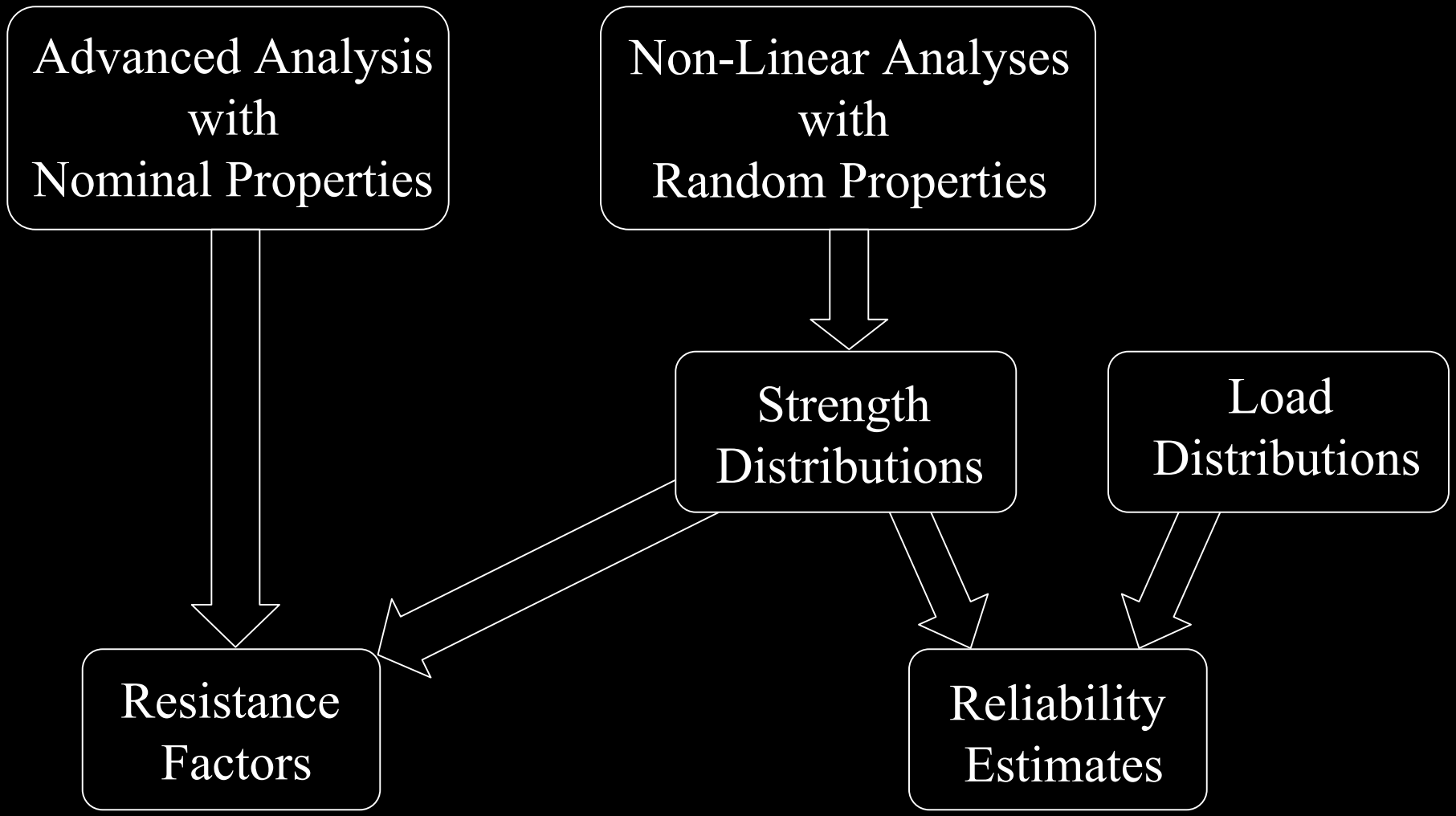



Member Sizes by:

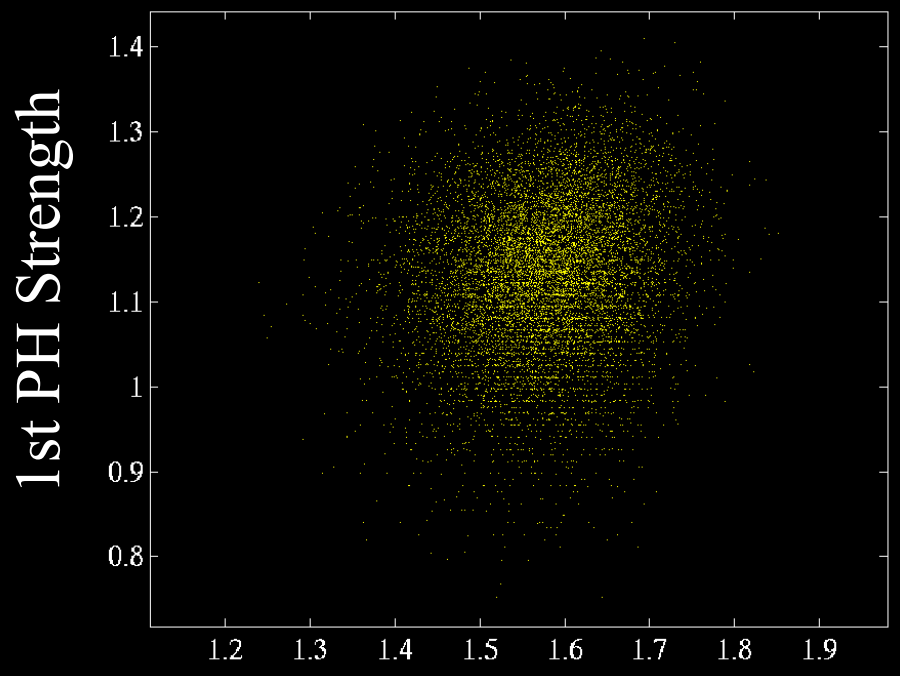
LRFD

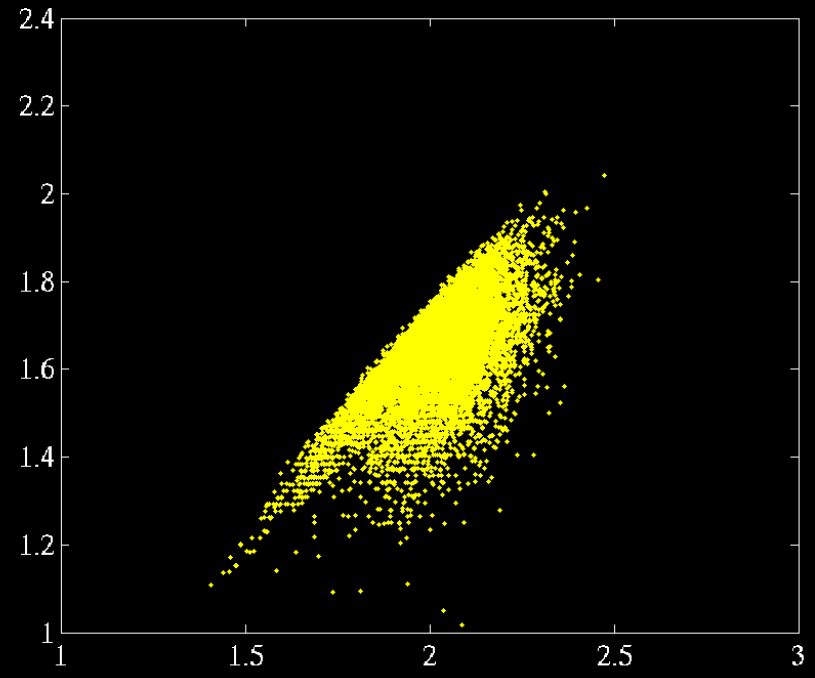
Advanced Analysis

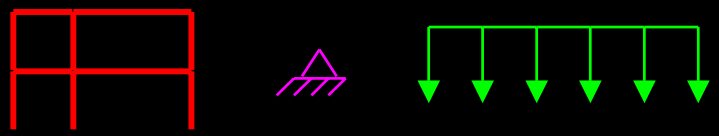
# Approach


Advanced Analysis with Nominal Properties
Non-Linear Analyses with Random Properties
Strength Distributions
Load Distributions
Resistance Factors
Reliability Estimates

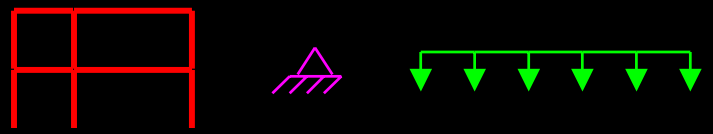
# System vs. Member Limit State



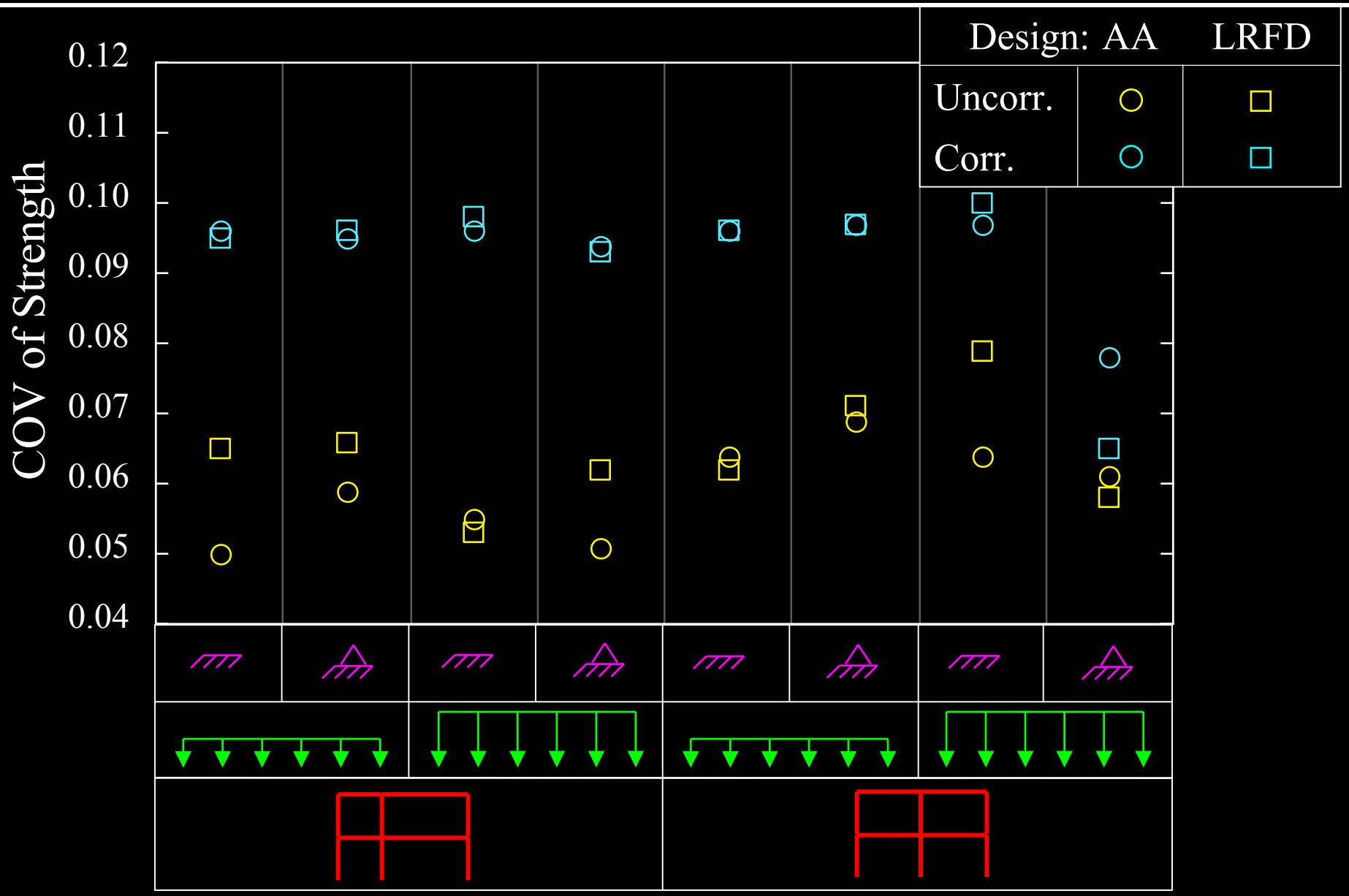



Uncorrelated $F_y$
AA Design



Uncorrelated $F_y$
LRFD Design

# COV of Strength at Plastic Collapse



# Reliability at Plastic Collapse