Reliability implications of advanced analysis in design of steel frames

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Advanced Analysis

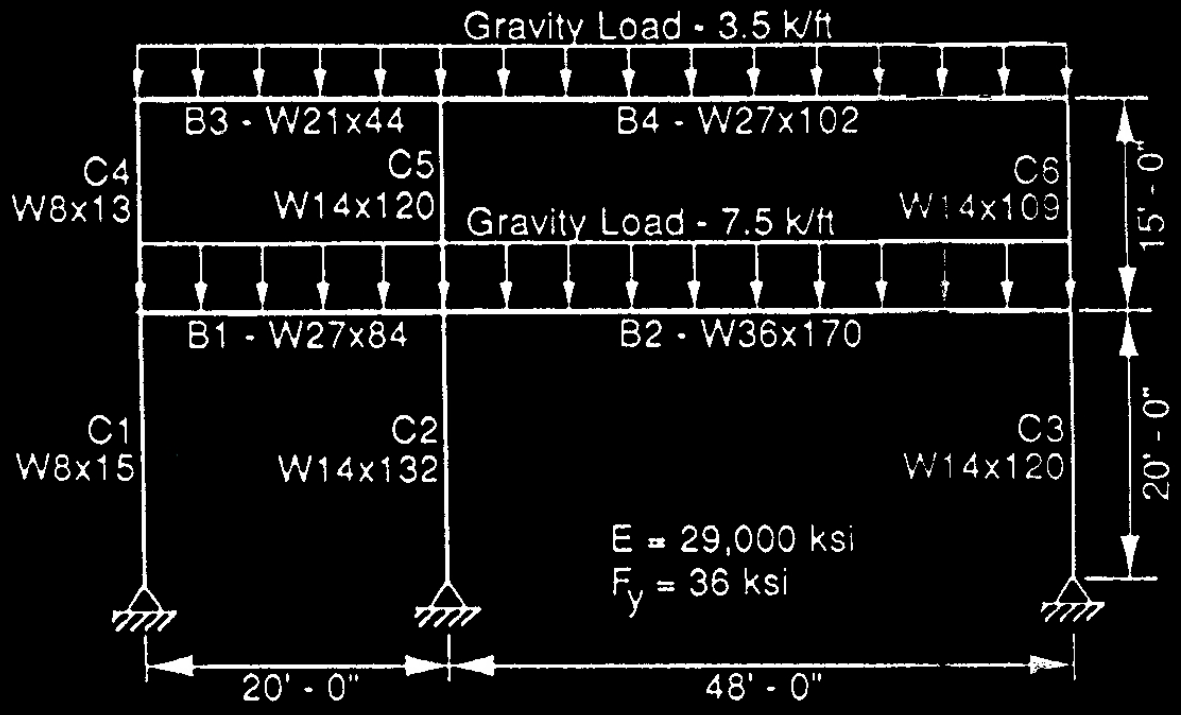
- Non-Linear Structural Analysis
  - e.g. Inelastic materials, P-Δ effects, fiber elements
- System Behavior
  - e.g. Frame stability, moment redistribution
- No member checking, etc., in design
- Analysis code: OpenSees (opensees.berkeley.edu)

Reliability & Advanced Analysis (AA)

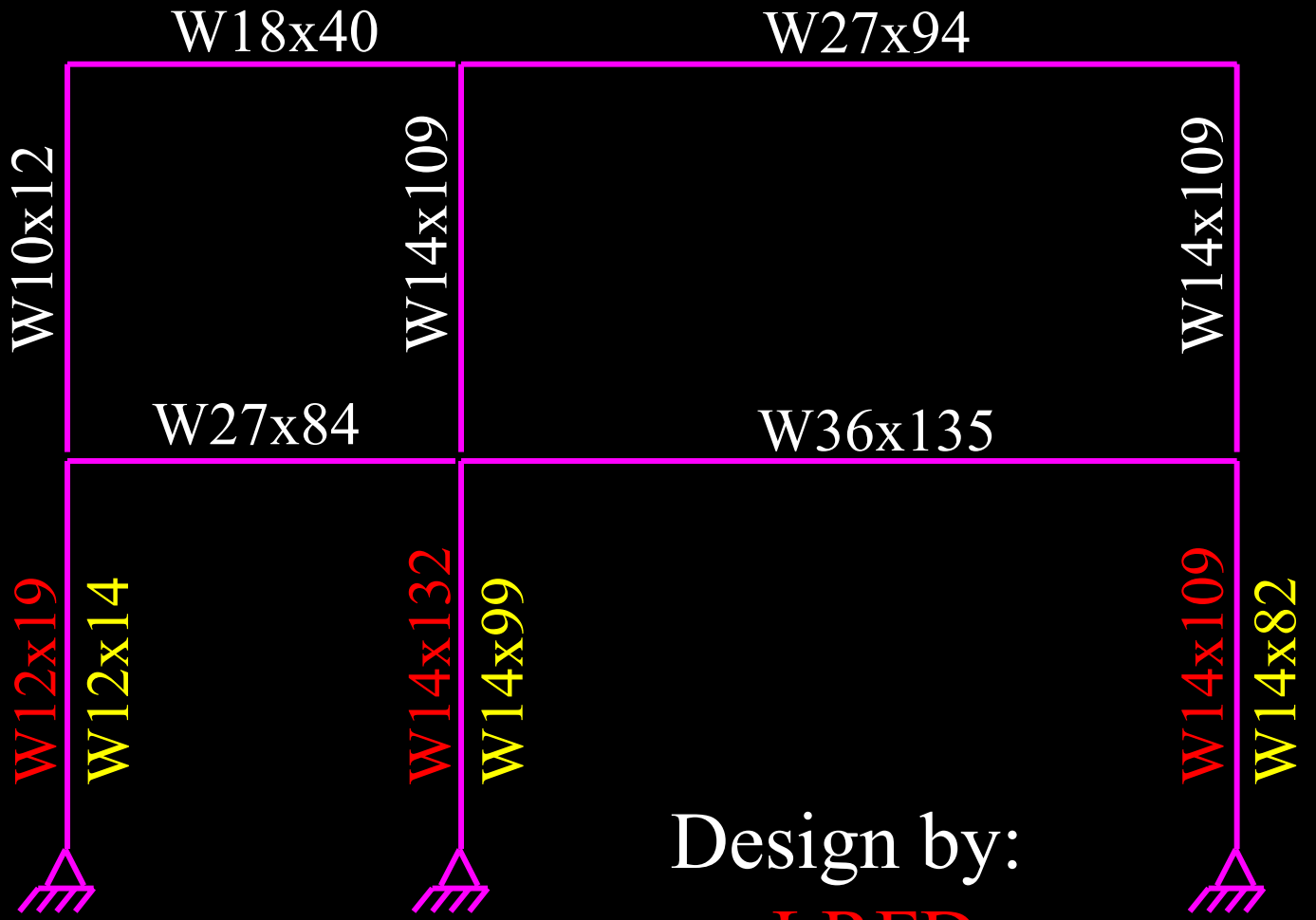
- Compare Reliability of Steel Frames Designed by the American AISC-LRFD vs. AA
- Compare Limit States
  Member (AISC-LRFD) vs. System (AA)
- Calculate Resistance Factors for AA
- Loads (D, L) and F_y random in our analysis

Frames for Study

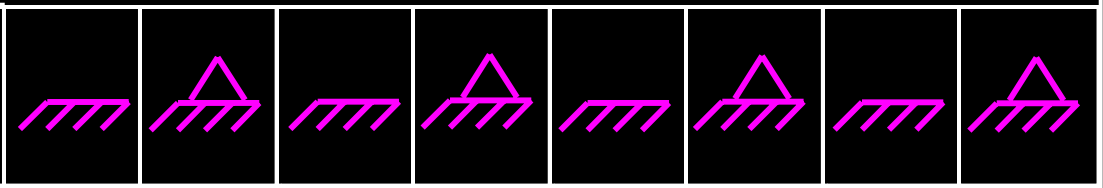
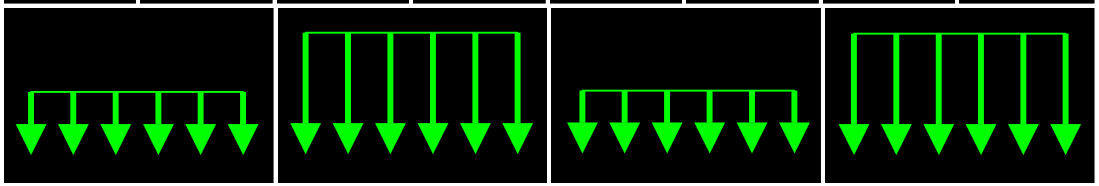
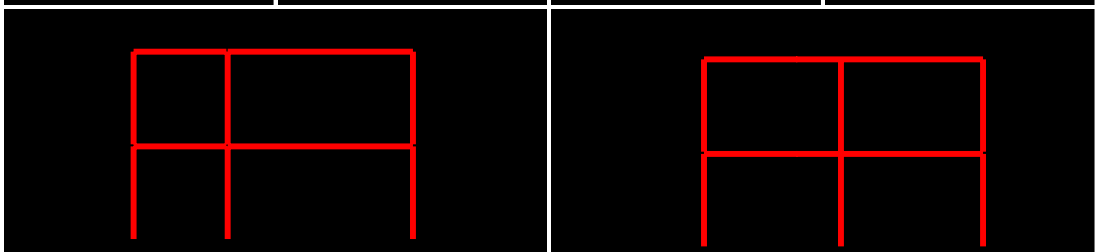
- Steel Frames from Ziemian et al. (1992)
- Designed by both AISC-LRFD (1986) and AA
- AA Design saves ~12% by weight



Member Size Comparison

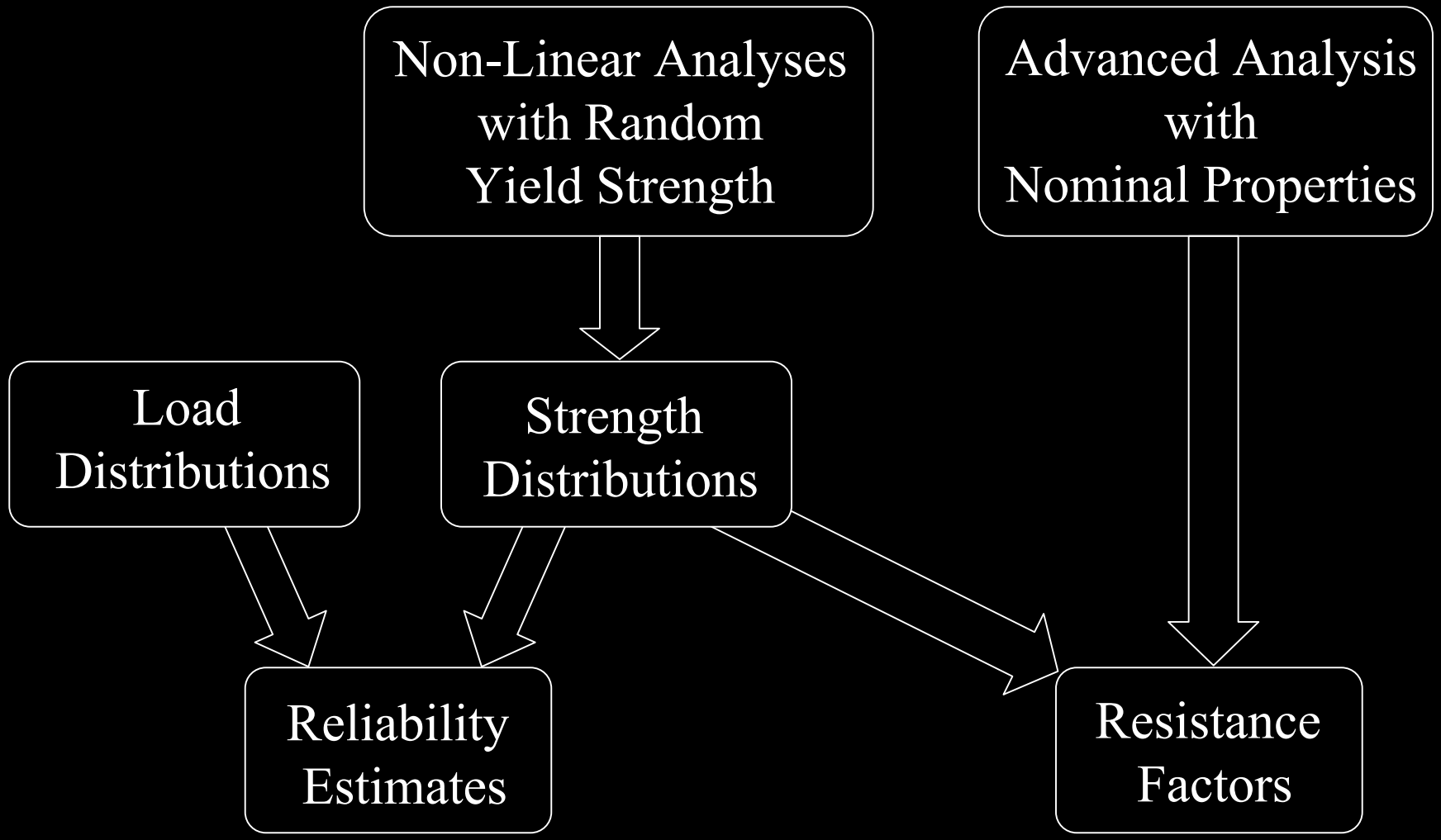


Frames for Study

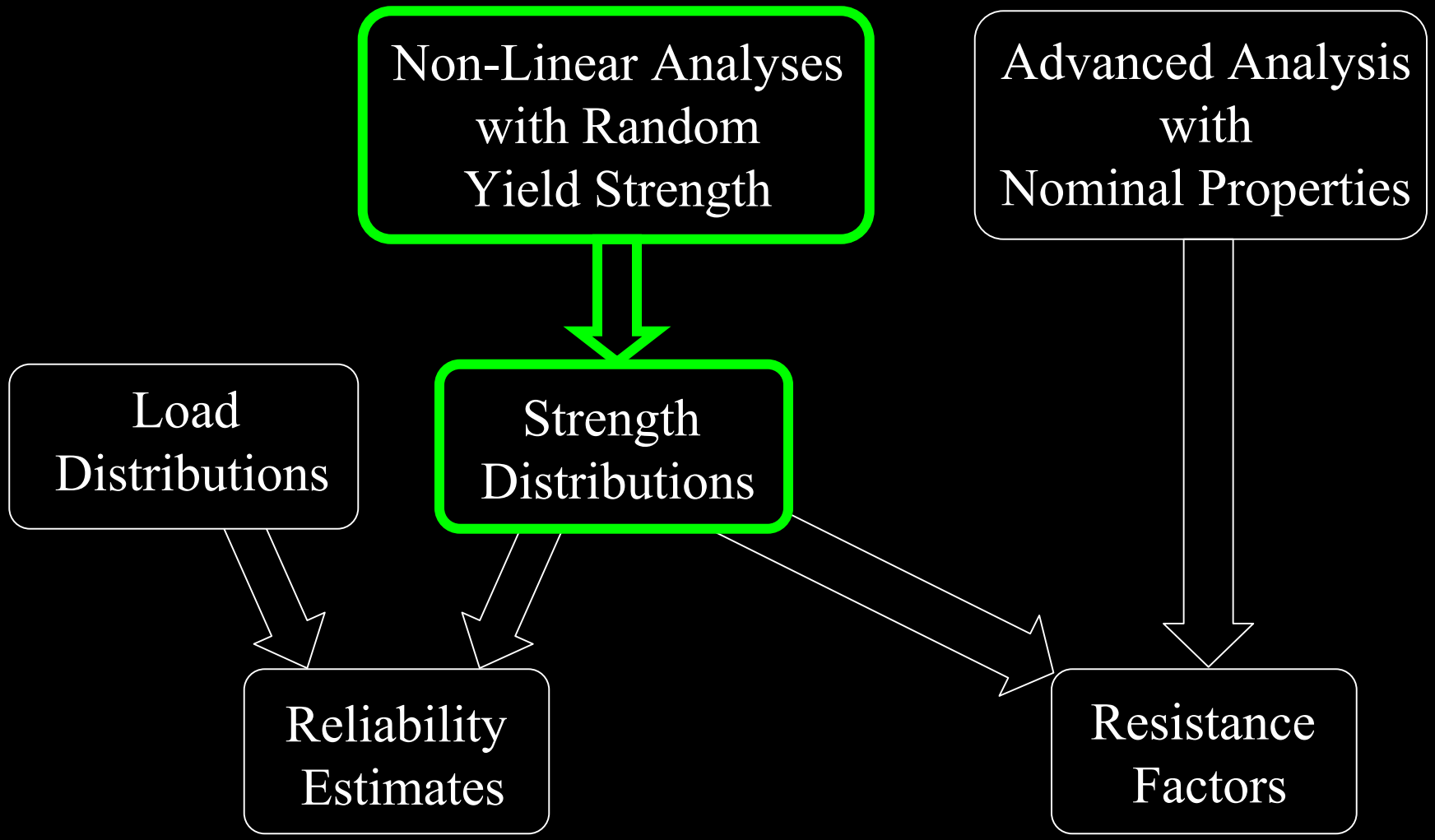
1. Member Sizes:	LRFD or AA
2. Yield Strength:	Uncorrelated and Correlated
3. Base Fixity	
4. Gravity Load	
5. Geometry	

Total = 32 Frames Analyzed

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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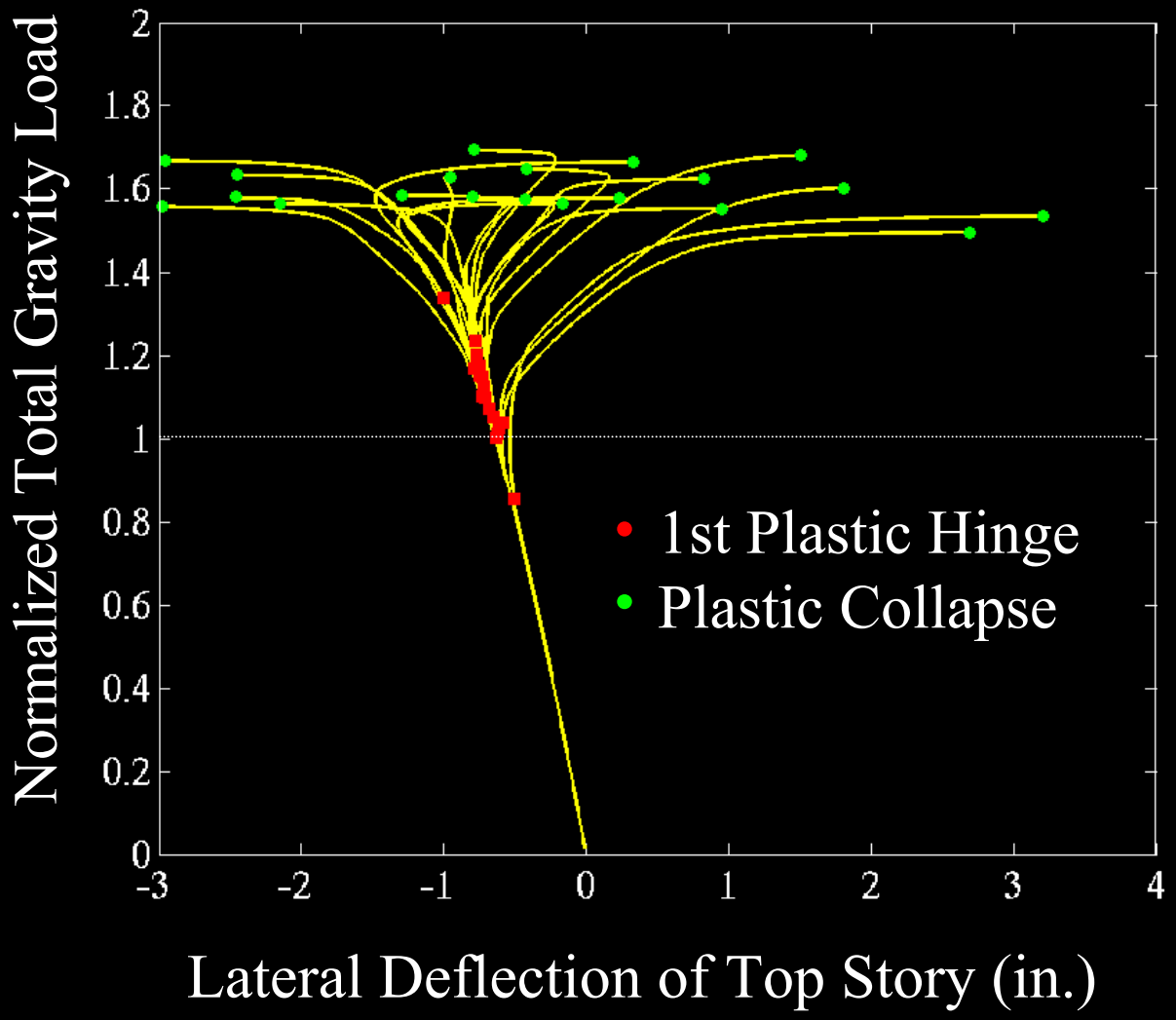
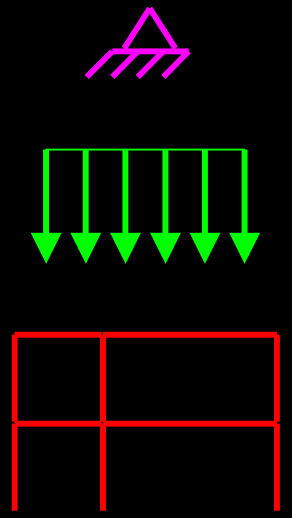
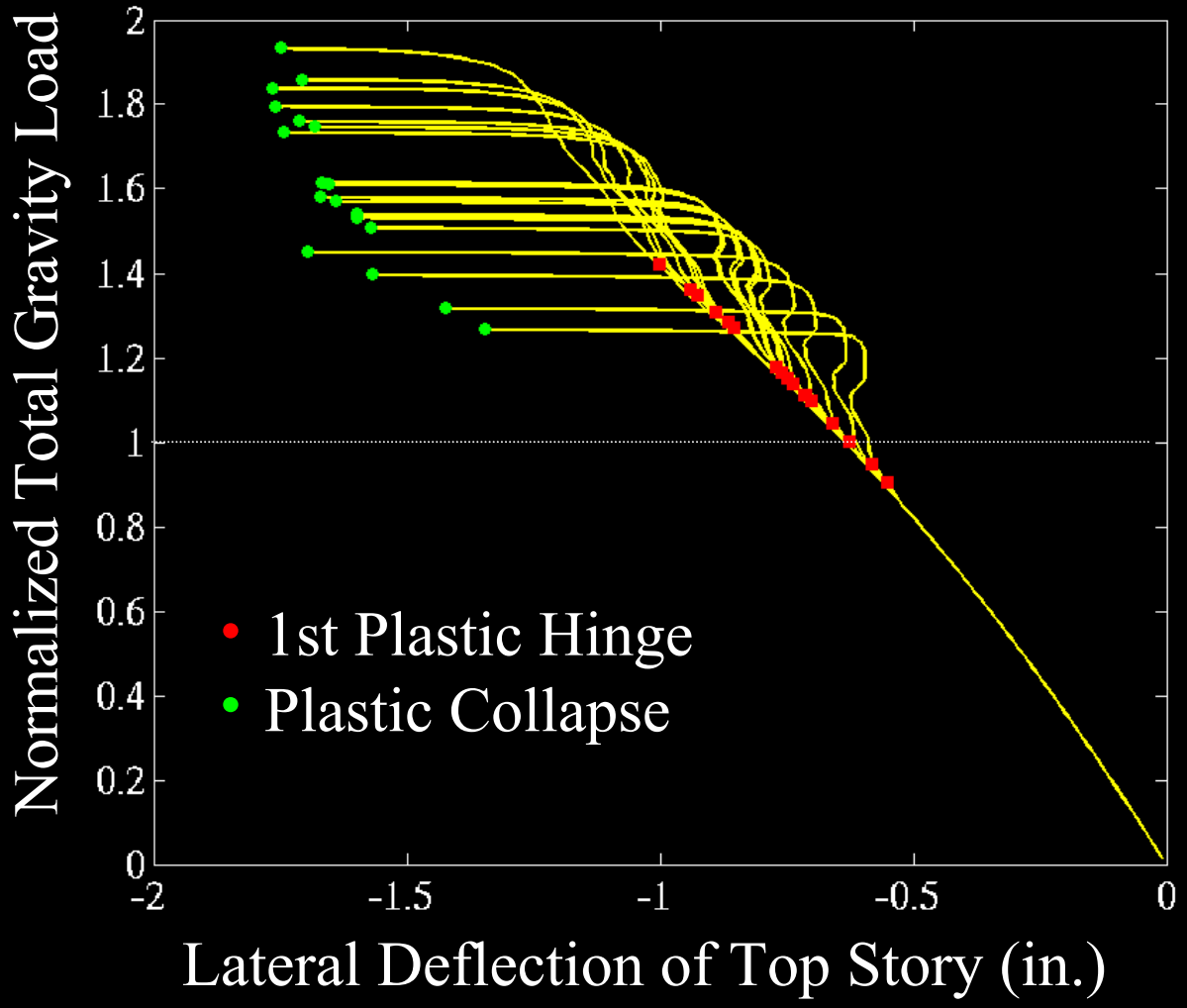
Load-Deflection Behavior



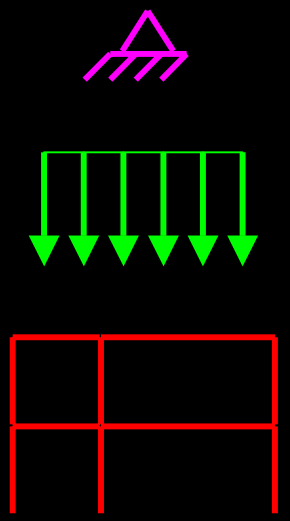
Uncorrelated F_y
AA Design



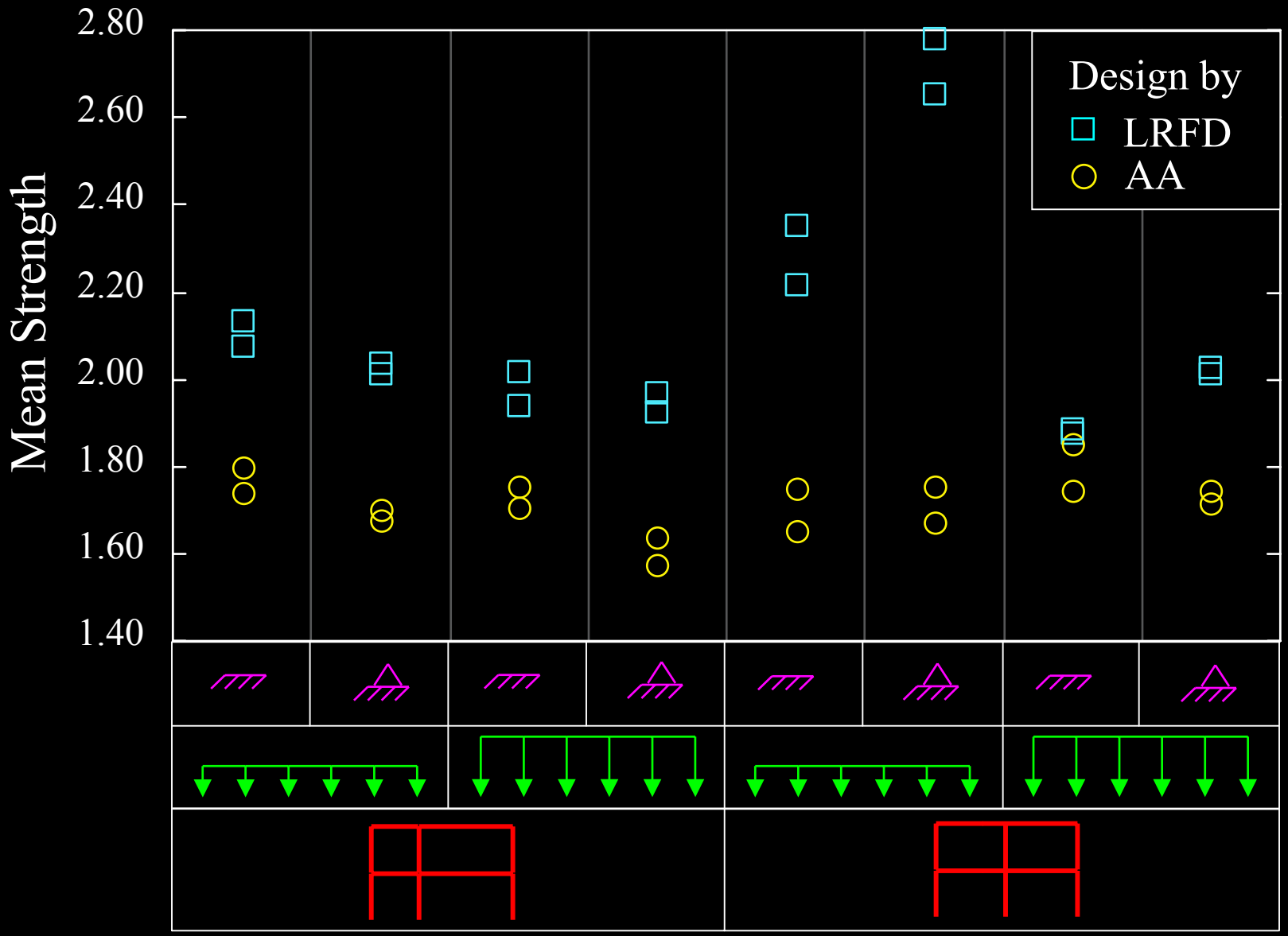
Load-Deflection Behavior



Correlated F_y
AA Design



Mean Strength at Plastic Collapse



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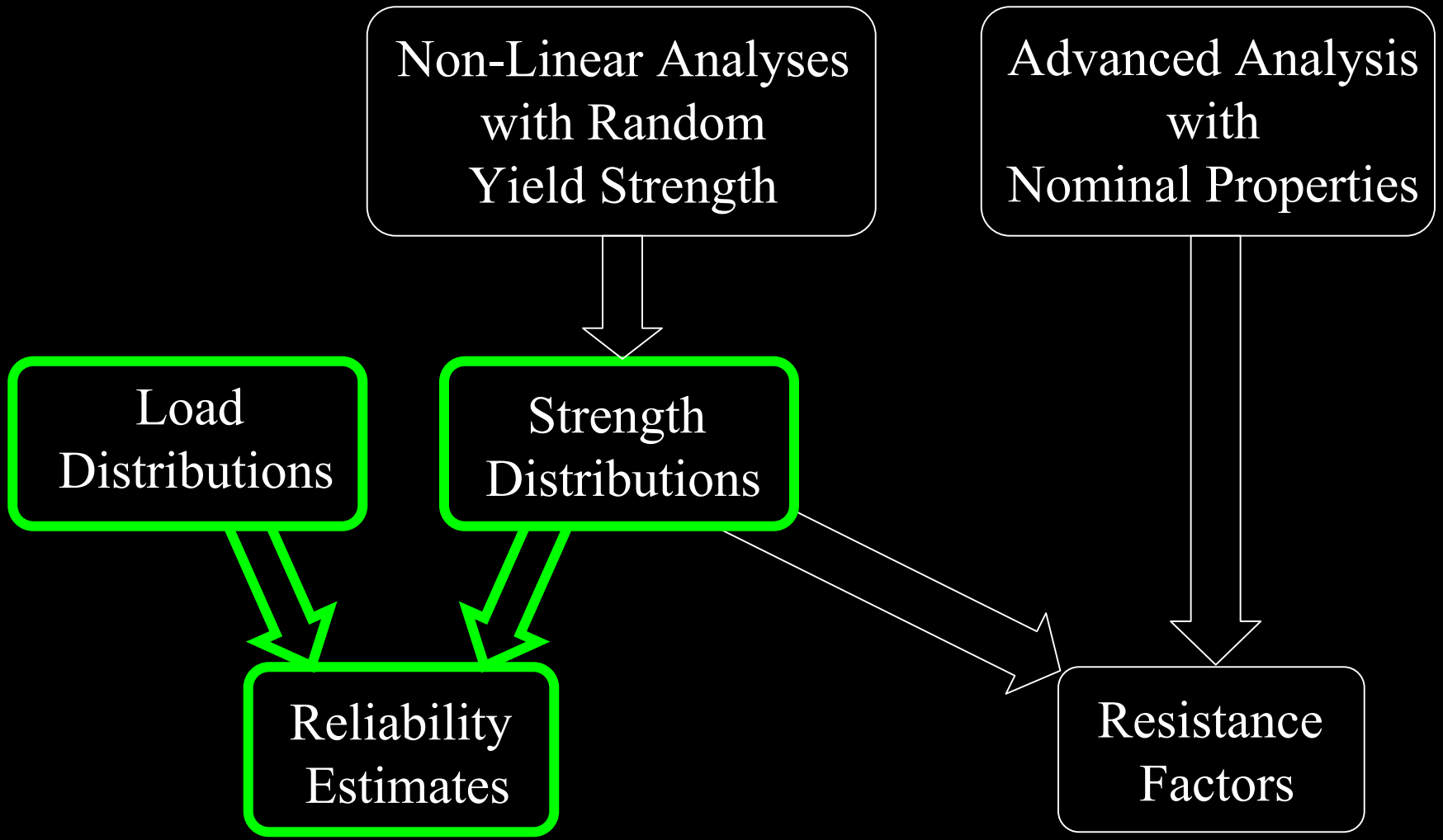
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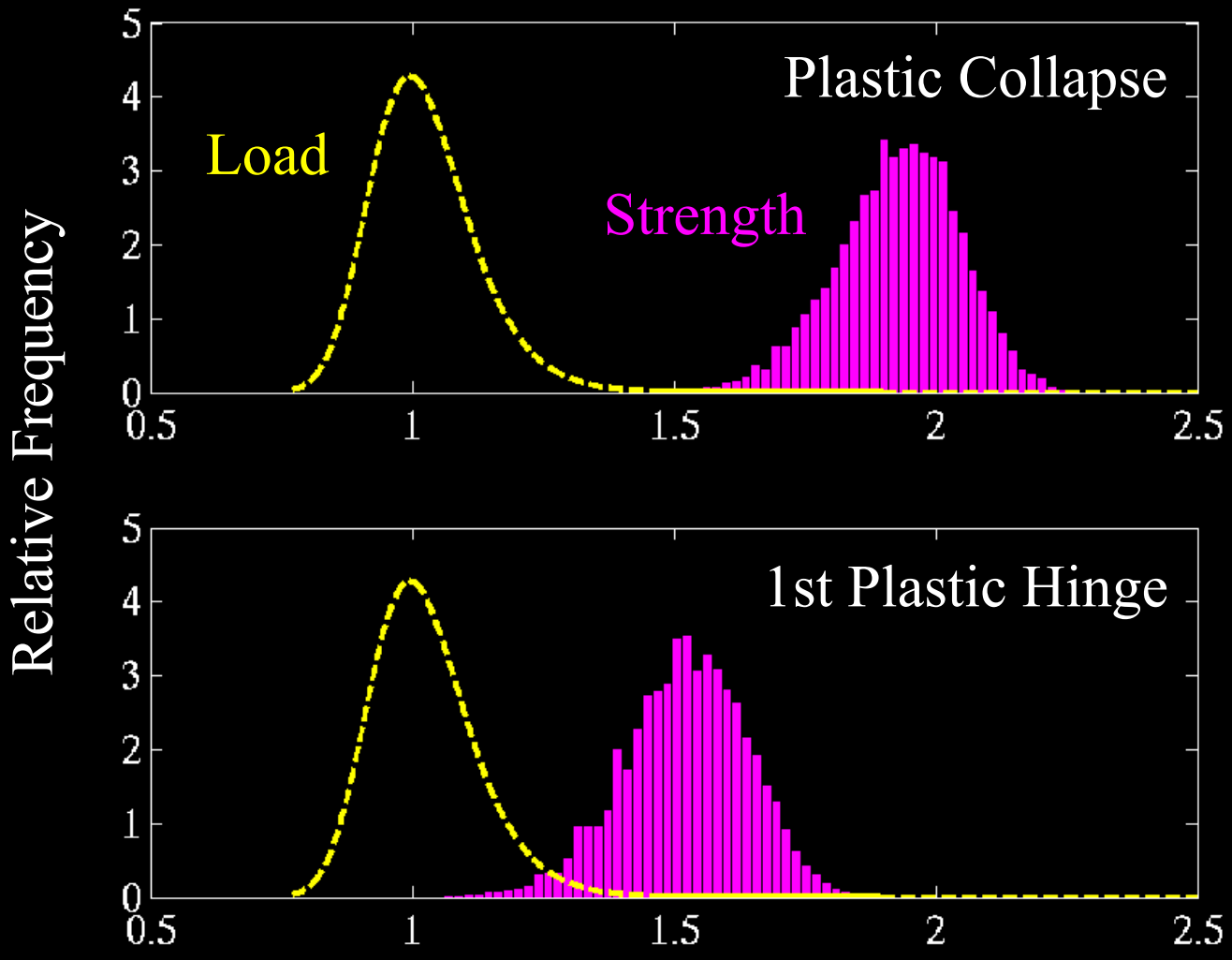
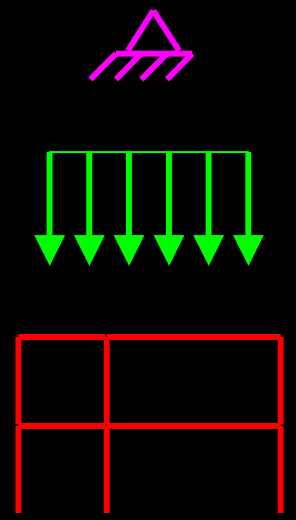
Strength Distributions

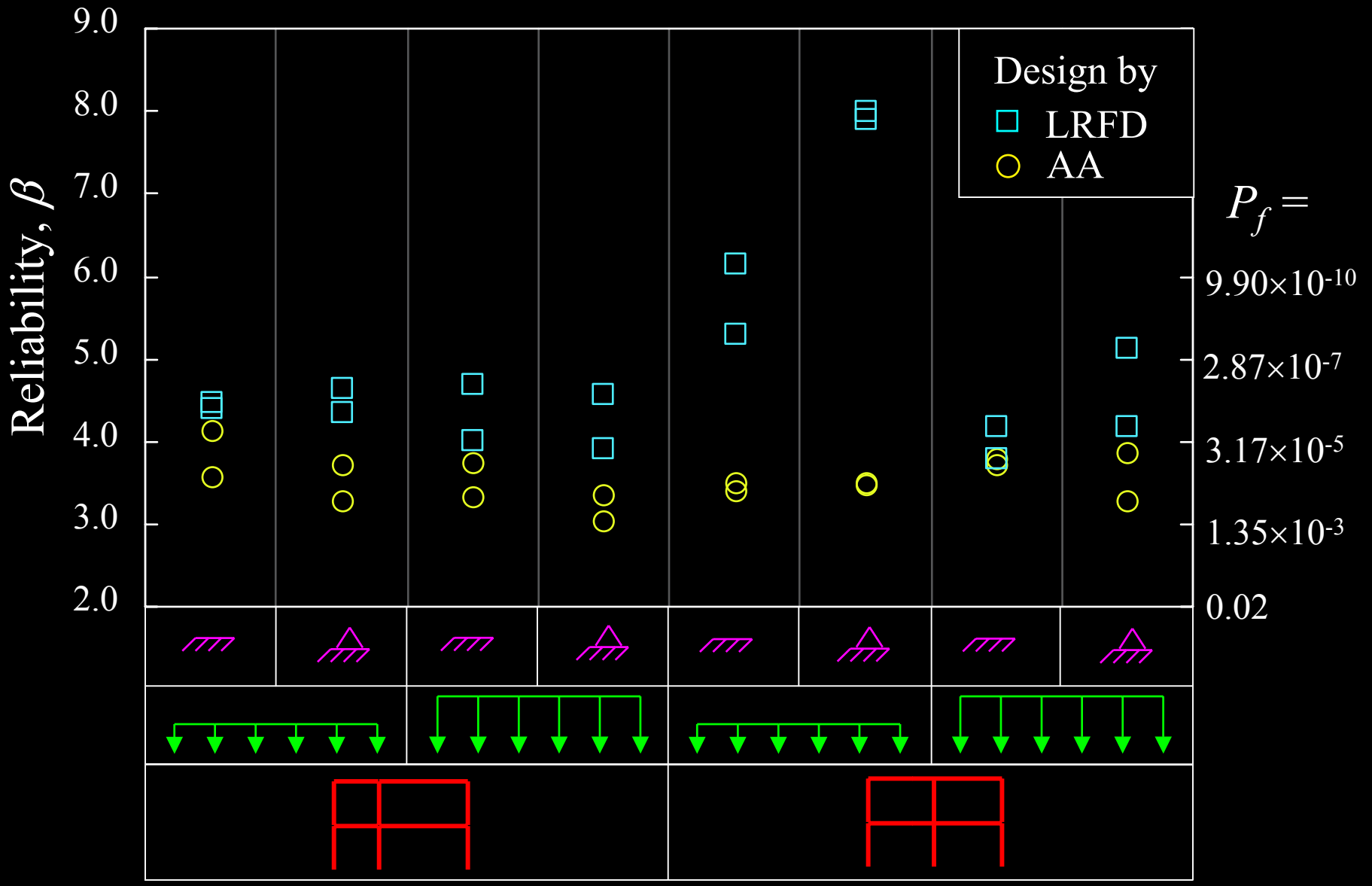


Uncorrelated F_y
LRFD Design

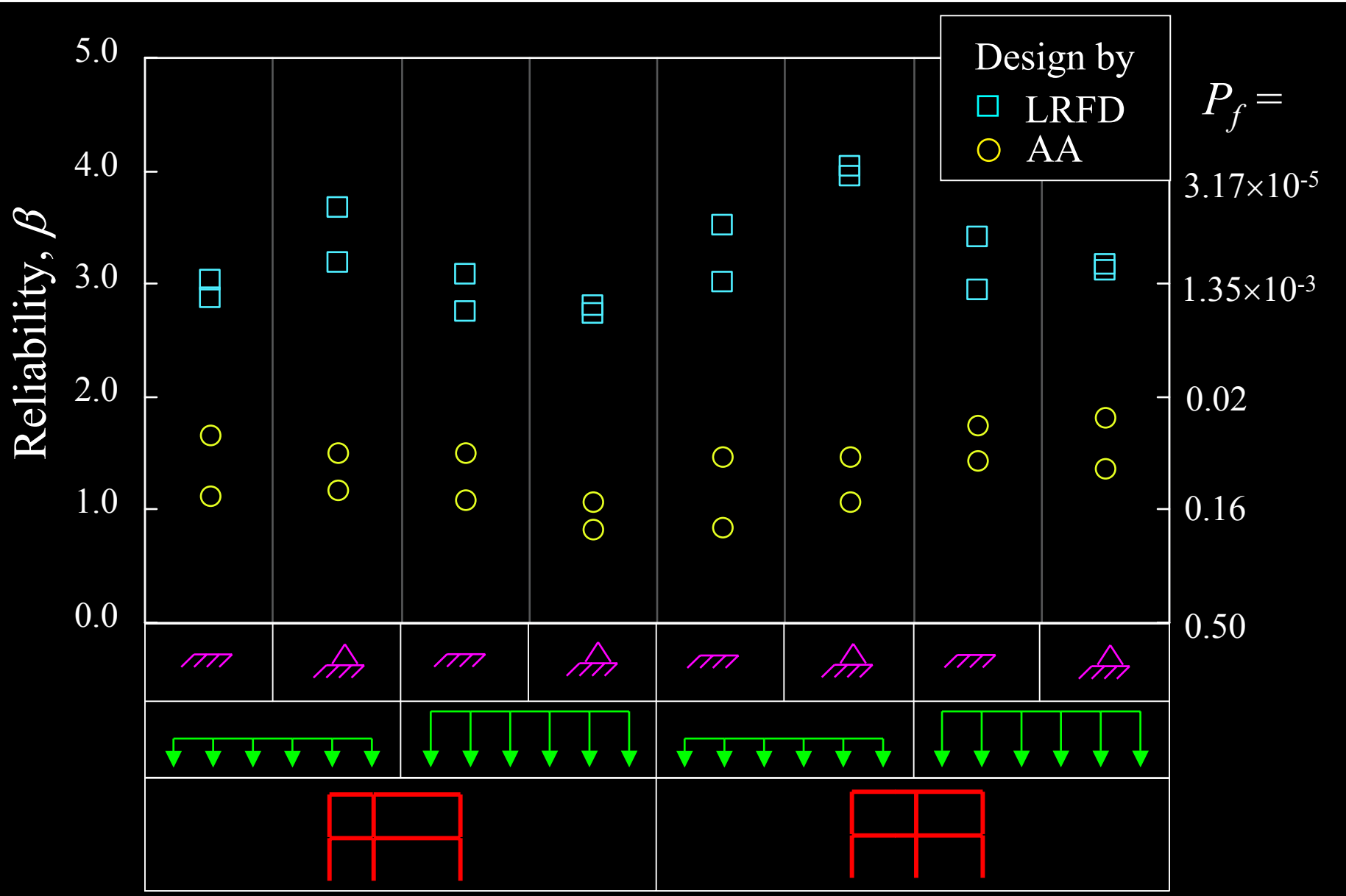


10,000 samples

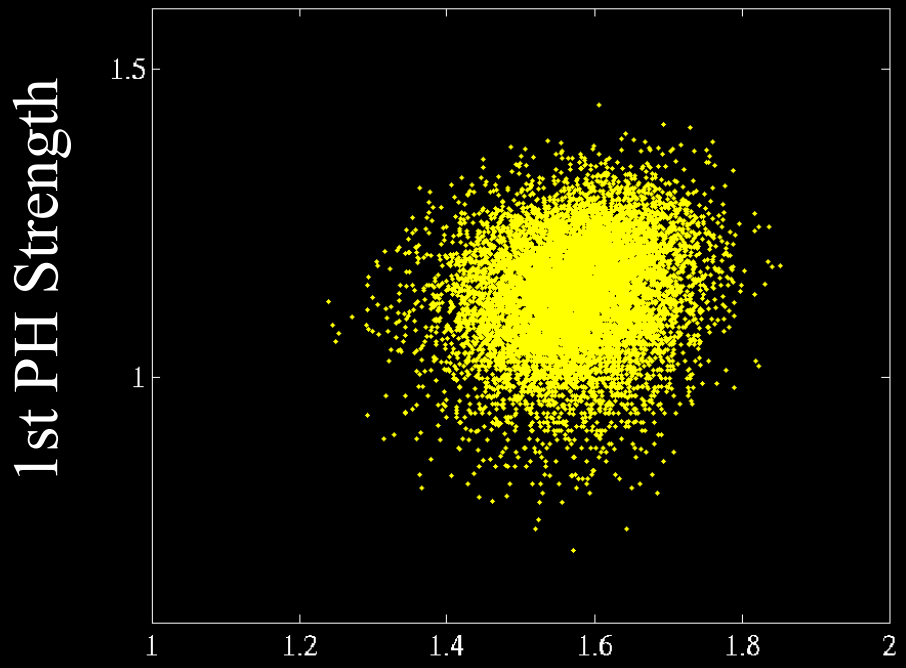
Reliability at Plastic Collapse

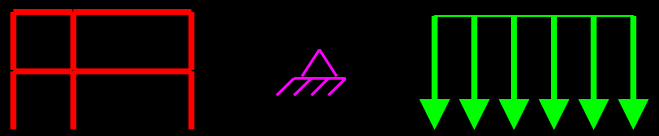


Reliability at 1st Plastic Hinge



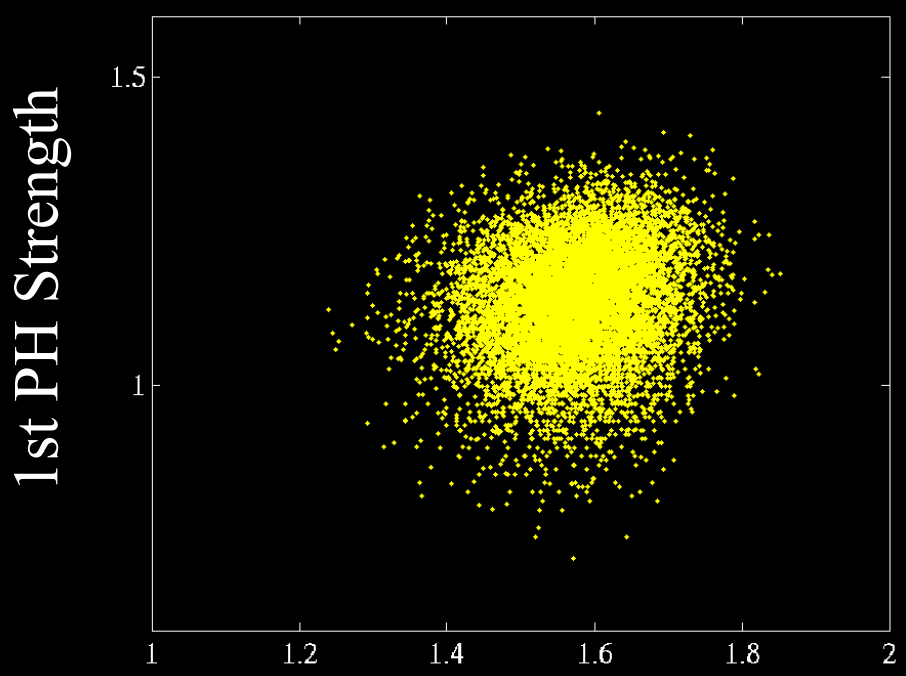
Member vs. System Limit State

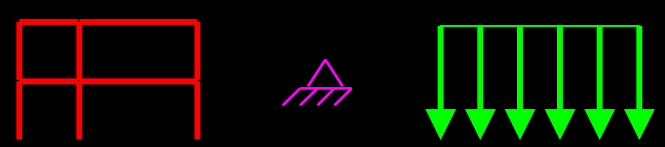




Uncorrelated F_y
AA Design

Member vs. System Limit State





Uncorrelated F_y
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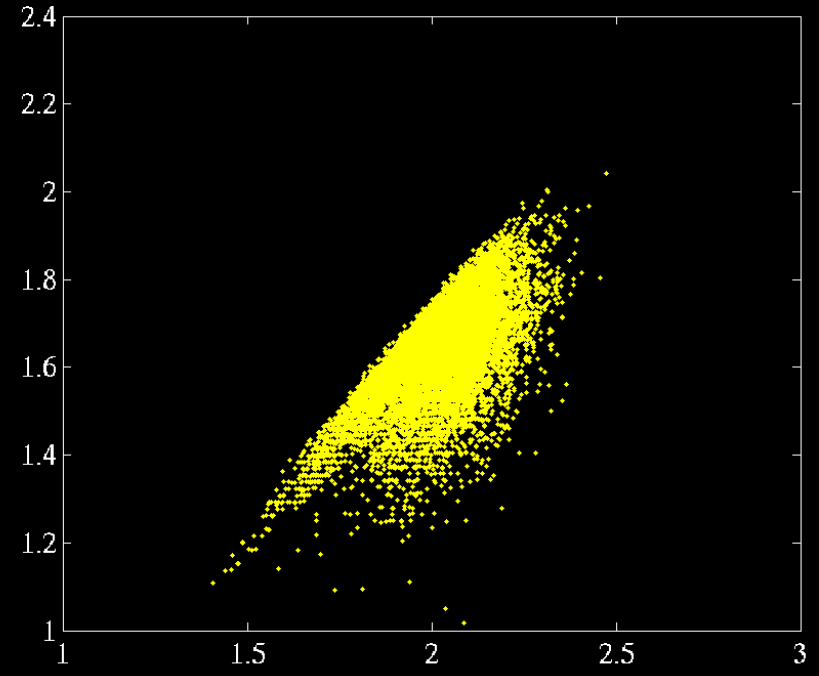
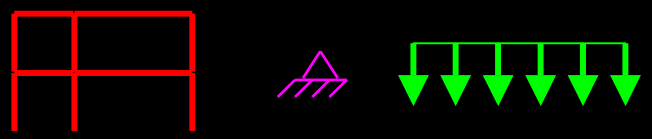
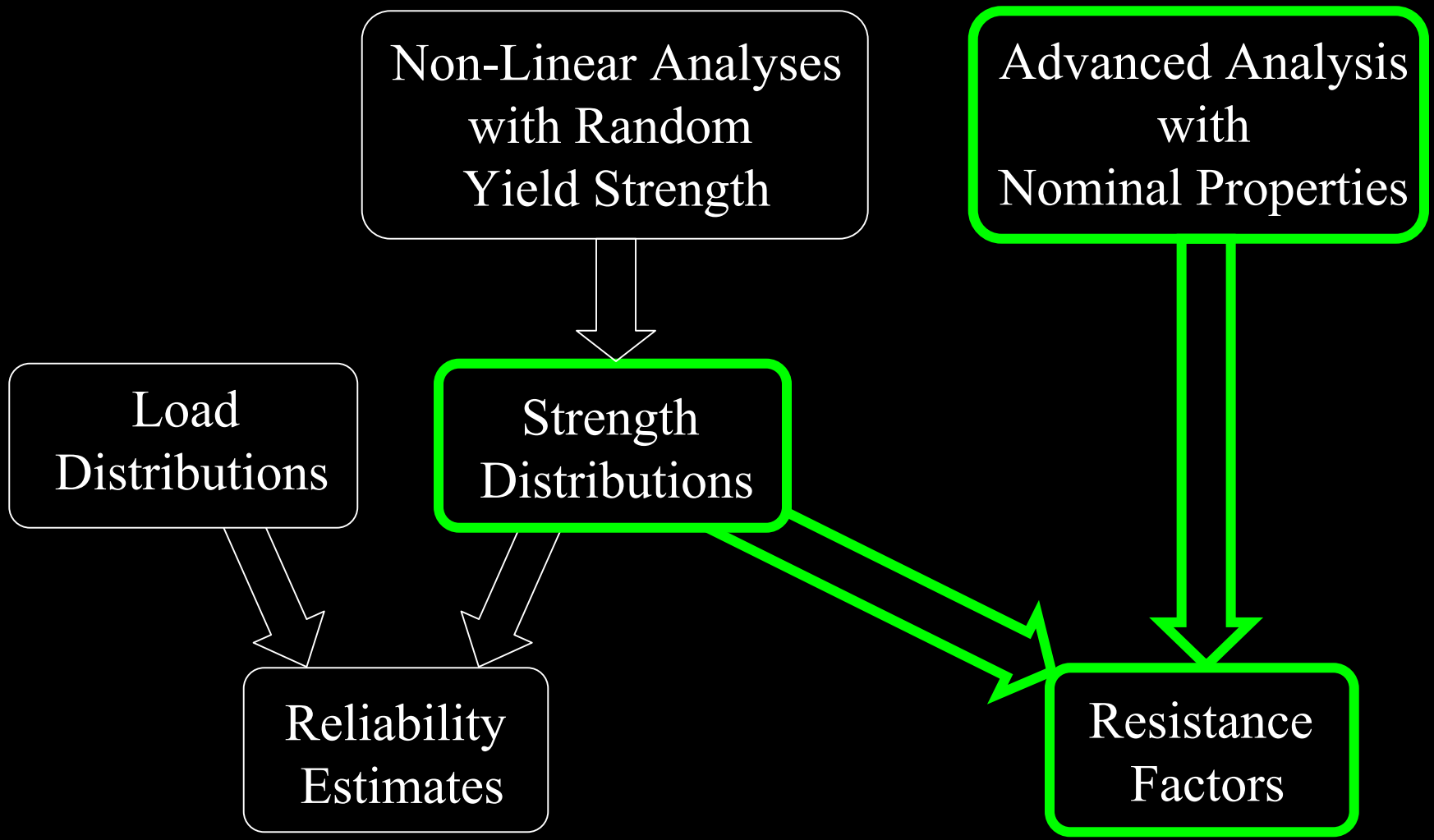




Uncorrelated F_y
LRFD Design

Overview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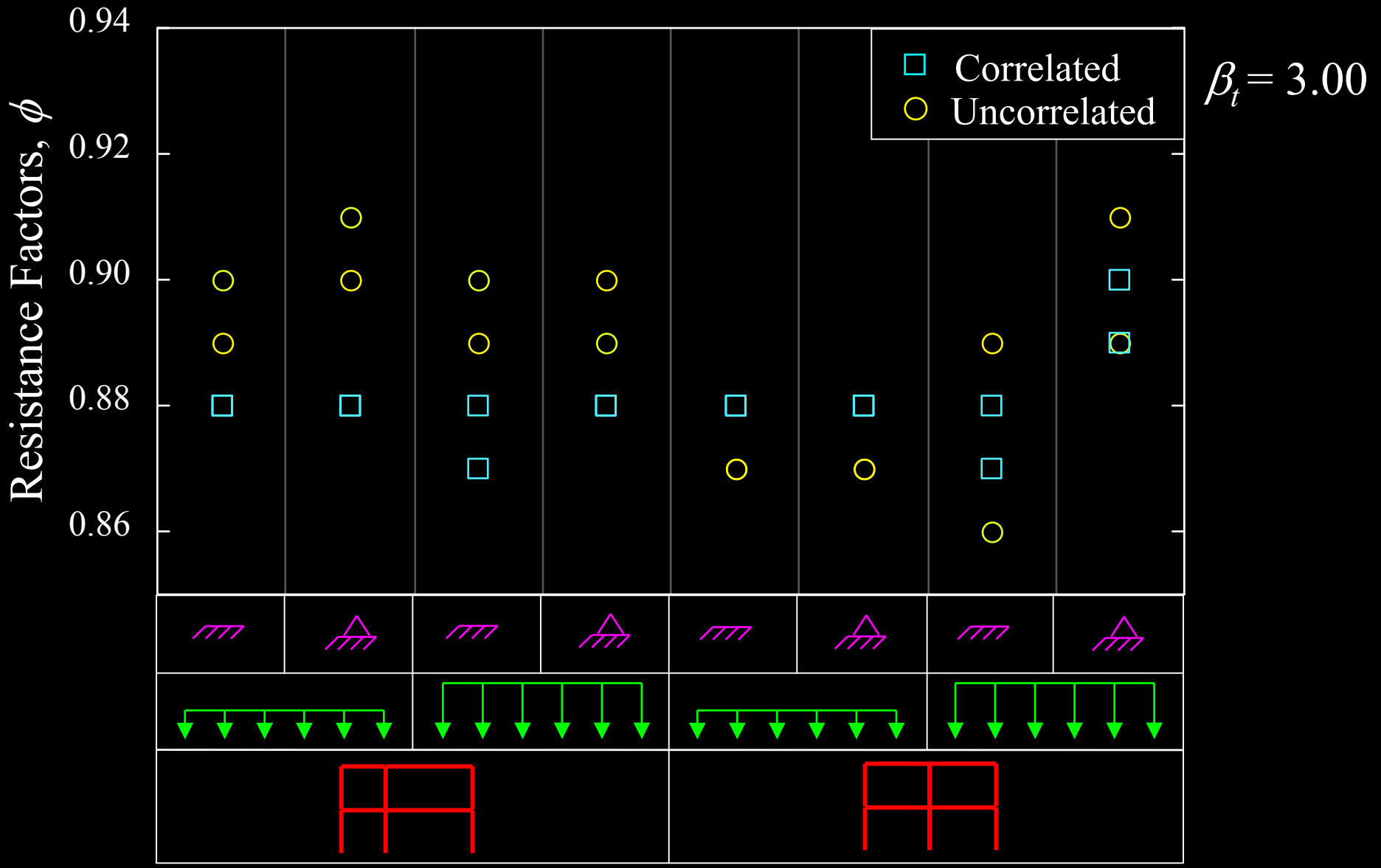
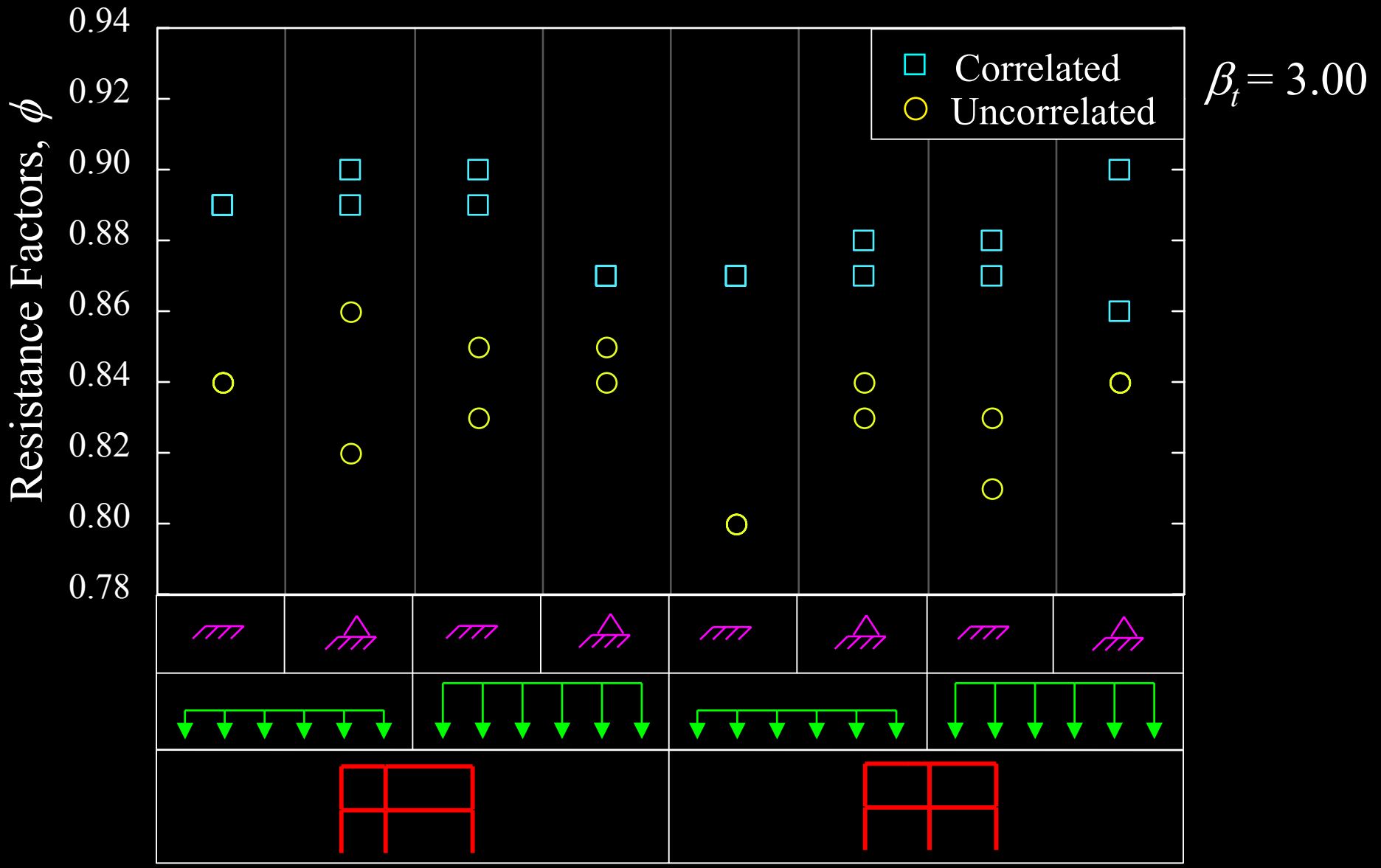
Resistance Factors for AA at PC



Resistance Factors for AA at 1st PH



Conclusions

- Probabilistic Basis for Advanced Analysis Resistance Factors

- No Simple Transformation from Member Design [Reliability] to System Design [Reliability]

- Increased Probability of 1st PH with Design by AA. Serviceability controls?

Frame Analysis Details

- Analysis code: OpenSees (opensees.berkeley.edu)
- Random Properties

  Yield Strength
  - 50 ksi (345 MPa) 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 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 (345 MPa) 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

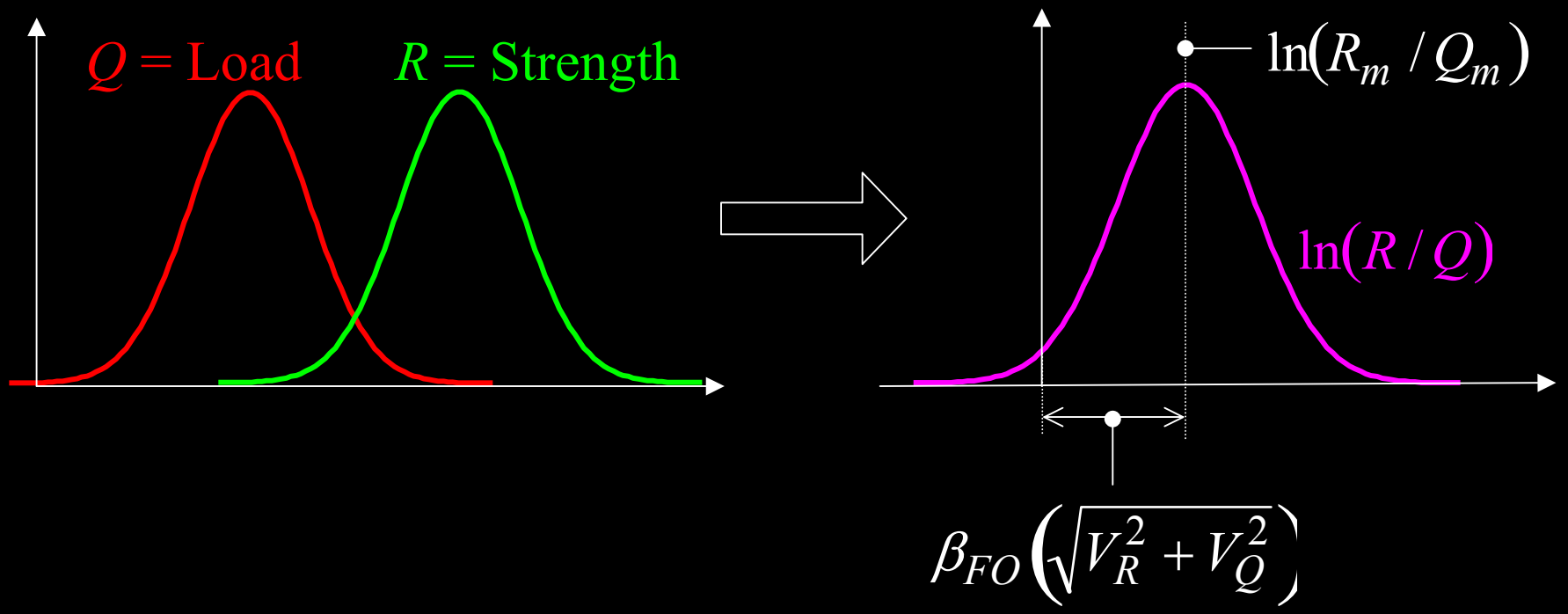
Frame Simulation Details

- 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

Future Work

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

Reliability and LRFD



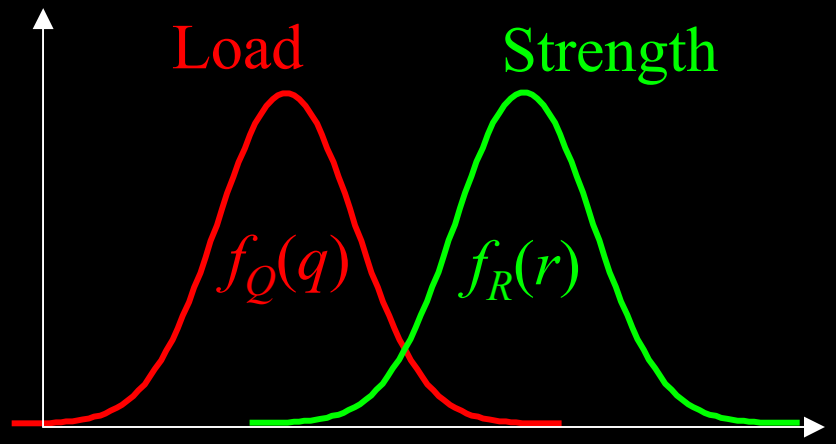
First-Order Reliability $\beta_{FO} = \dfrac{\ln(R_m / Q_m)}{\sqrt{V_R^2 + V_Q^2}}$

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

Resistance Factors

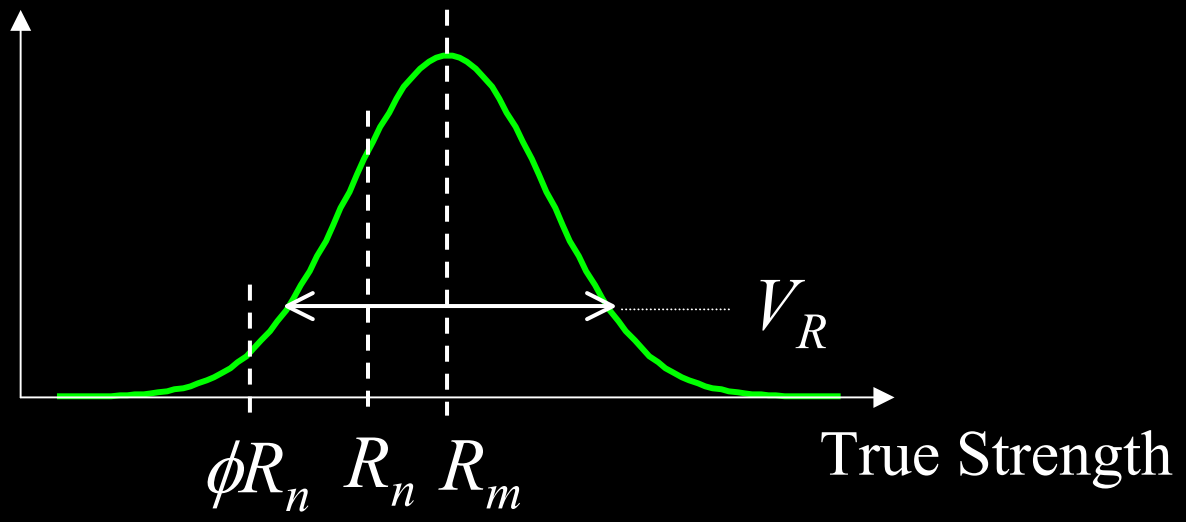
$$\phi = (R_m / R_n)\exp(-0.55\beta_t V_R)$$

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

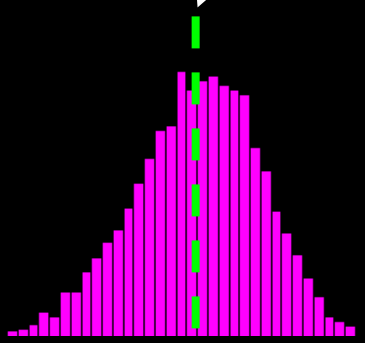
F = Fabrication

Resistance Factors for AA

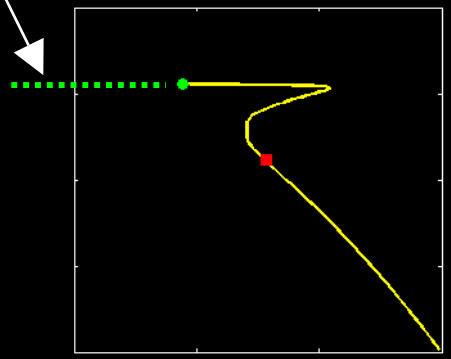
$$\phi = (R_m / R_n)\exp(-0.55\beta_t V_R)$$

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

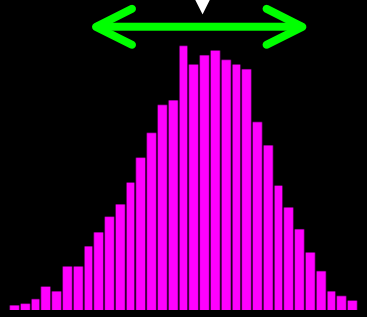
$$V_{B^{AA}} = \sqrt{V_{R^{AA}}^2 + V_F^2}$$



AA Strength Distribution

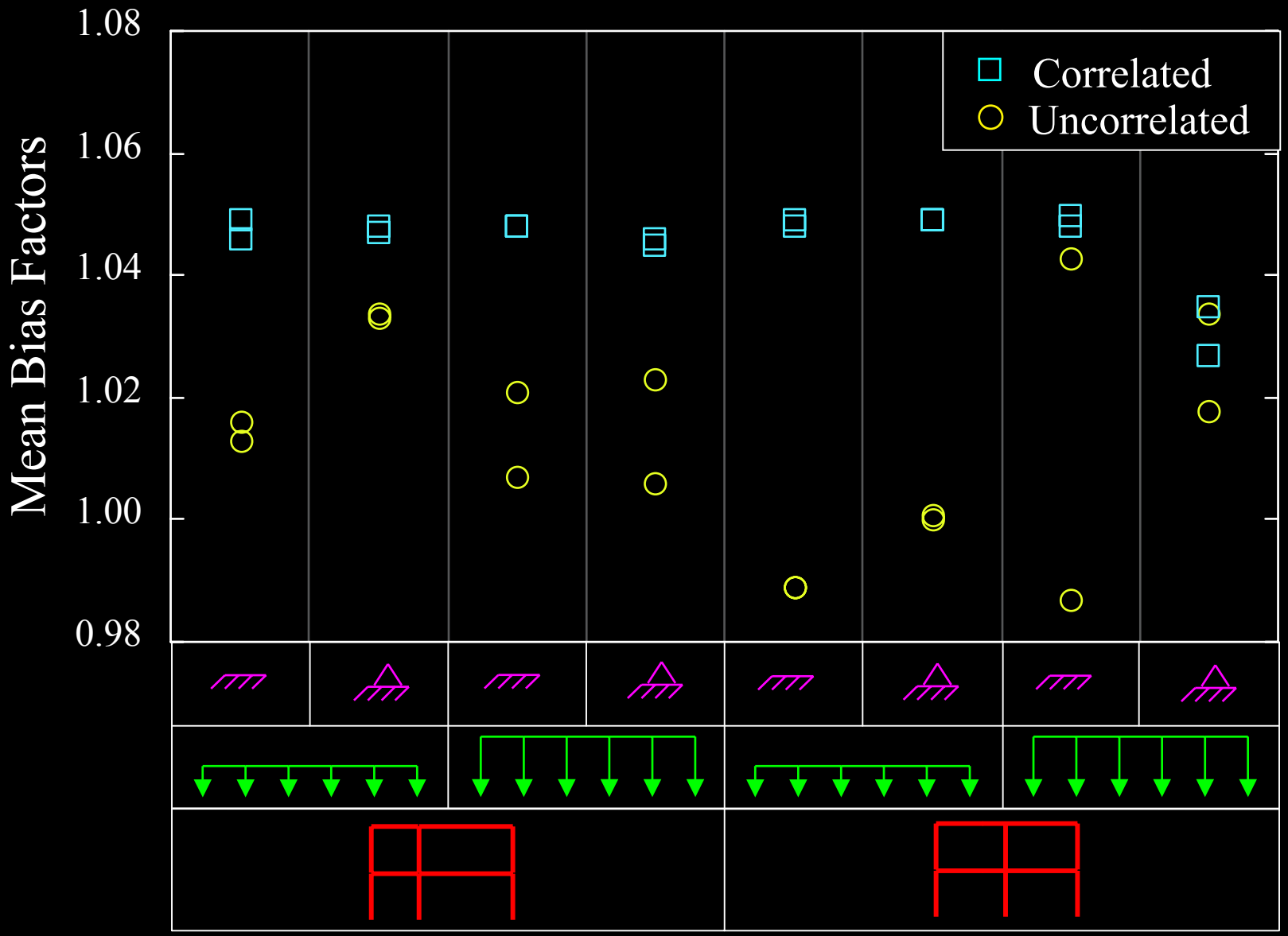


AA Nominal Strength



AA Strength Distribution

Mean Bias Factors

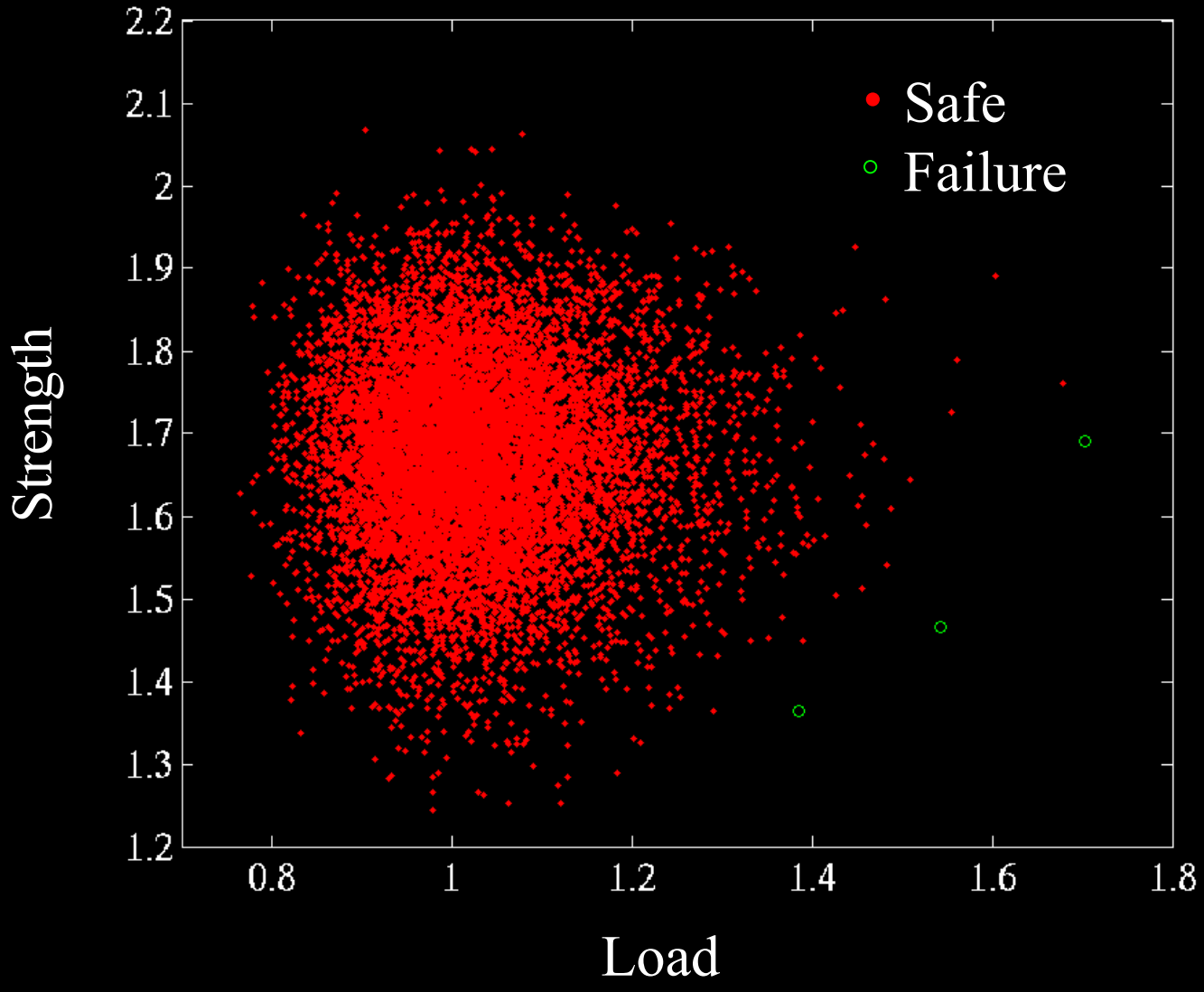


Summary of Resistance Factors

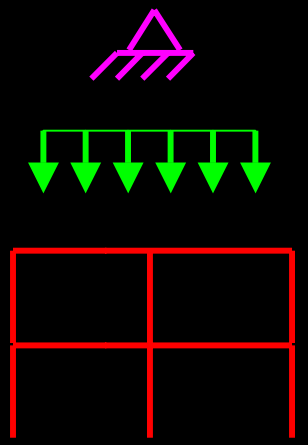
Limit State	Plastic Collapse		1st Plastic Hinge	
F_y	Uncorr.	Corr.	Uncorr.	Corr.
Min	0.86	0.87	0.80	0.86
Mean	0.89	0.88	0.83	0.88
Max	0.91	0.90	0.86	0.90

Target Reliability, $\beta_t = 3.00$

Reliability by Sampling



Uncorrelated F_y
AA Design



Reliability by Sampling

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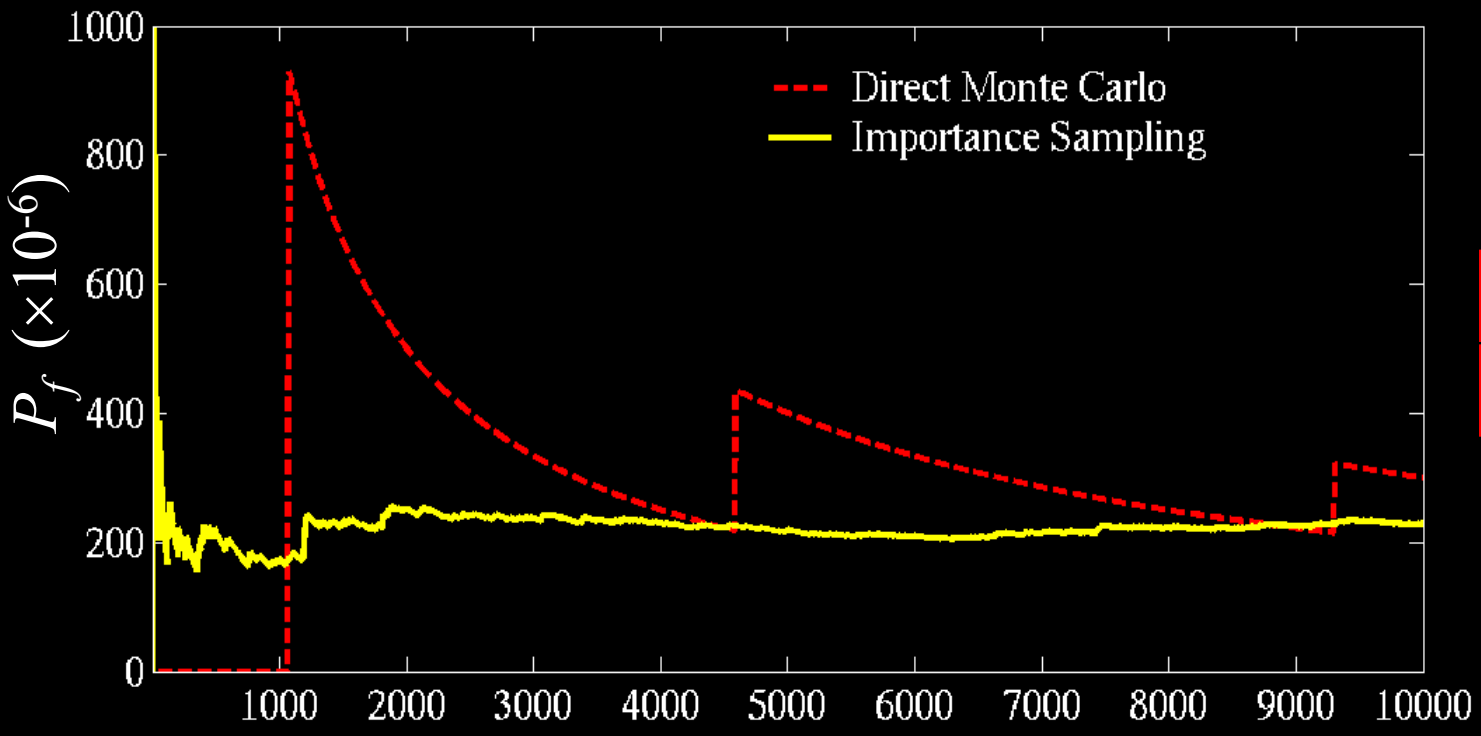

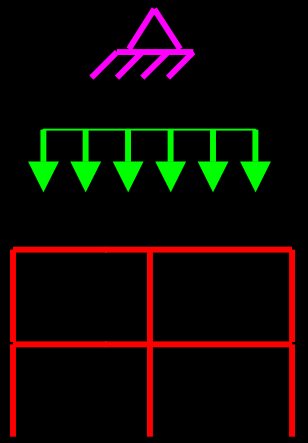

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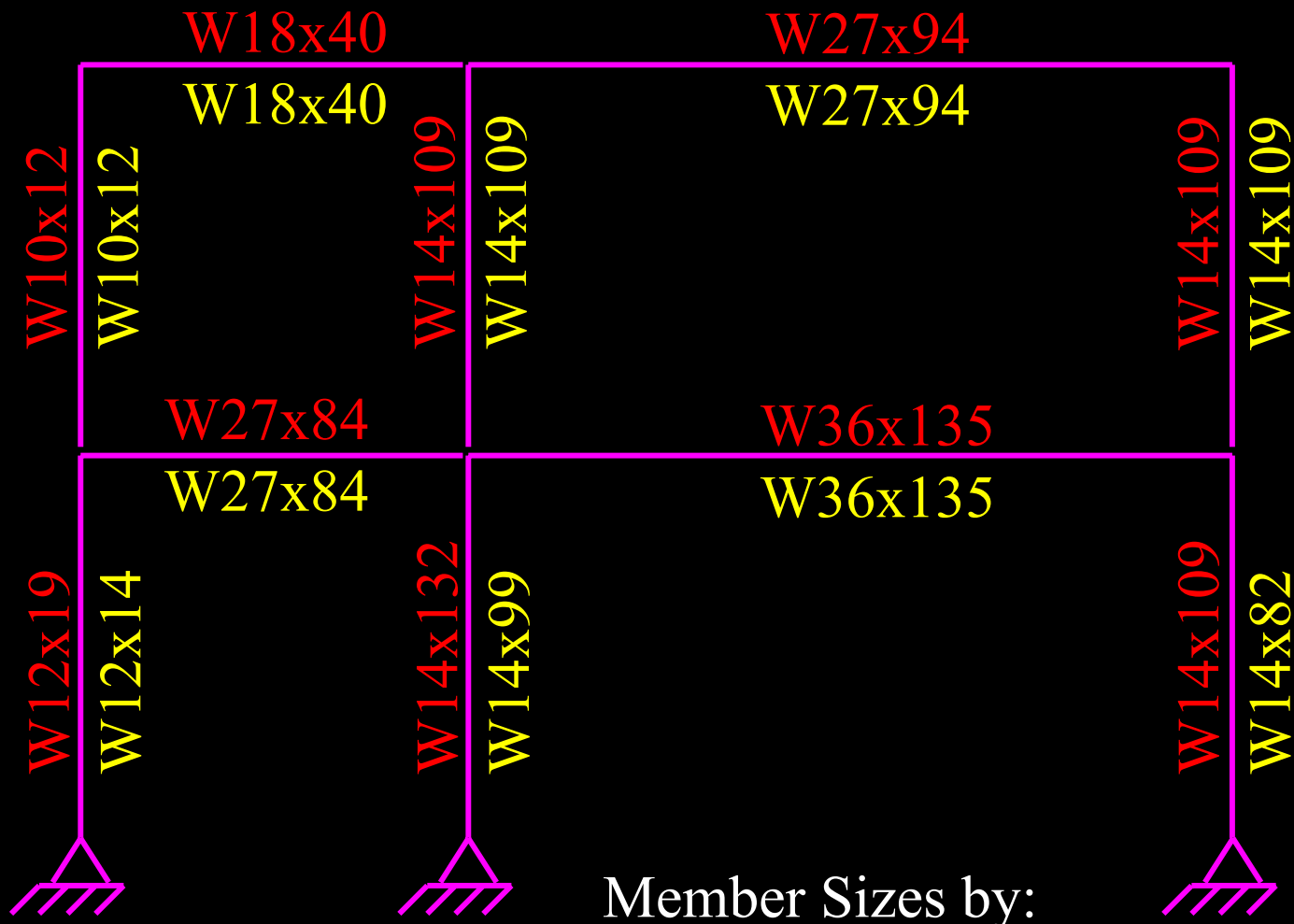
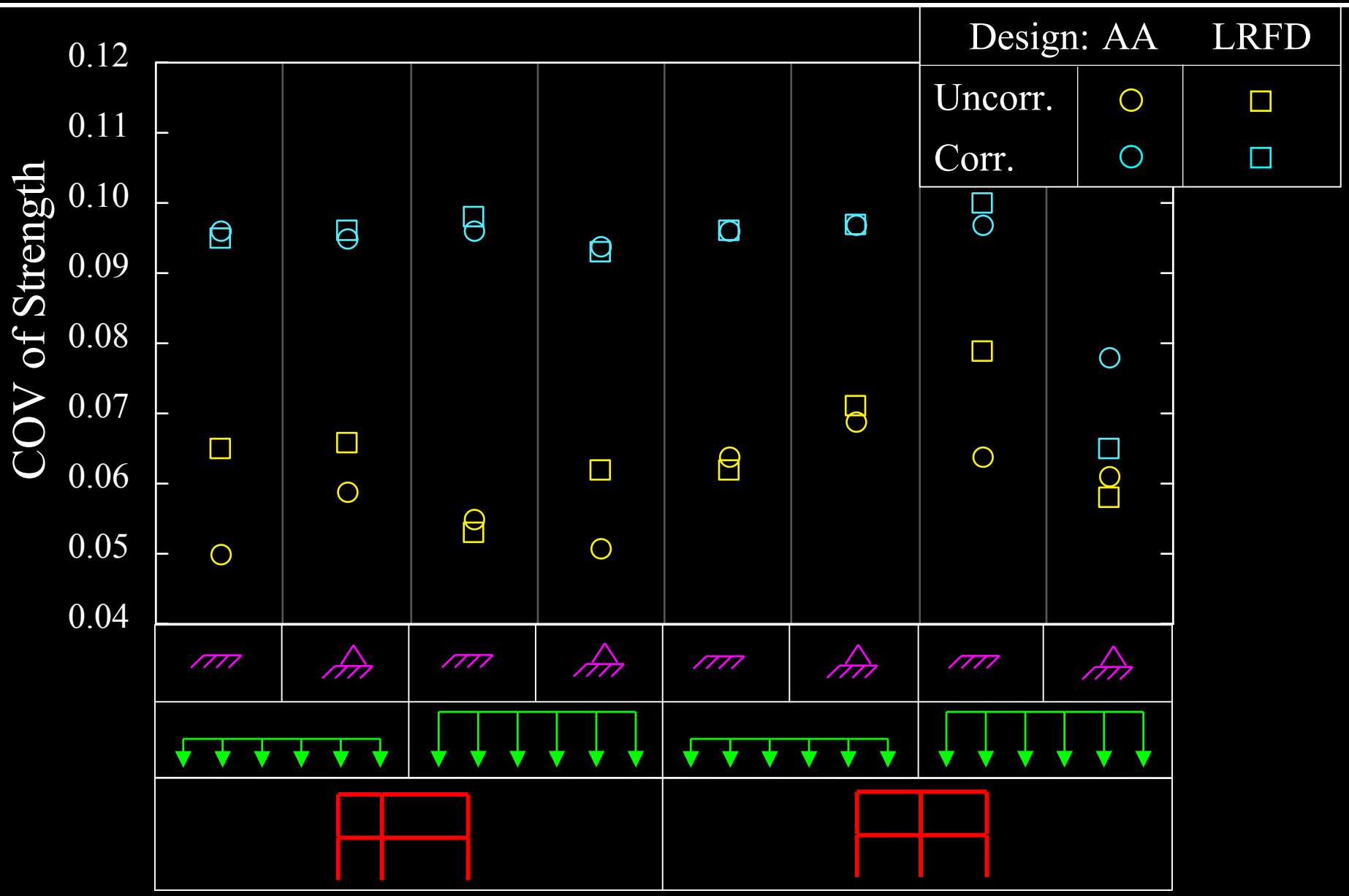


Member Sizes by:

LRFD

Advanced Analysis

COV of Strength at Plastic Collapse



Reliability at Plastic Collapse