On the Reliability of FRP Reinforced Concrete

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Chair, ACI Committee 440

Outline

- History of flexural design equations in ACI 440.1R
- Database
- Reliability analysis
- Results and ACI 440.1R

ACI 440

- ACI Committee on Fiber Reinforced Polymer Reinforcement
- Pertinent documents
  - ACI440.1R-06 – Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars
  - ACI440.5-08 – Specification for Carbon and Glass Fiber-Reinforced Polymer Reinforcing Bars
  - ACI440.6-08 – Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars.
  - ACI440.2R-08 – Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
  - ACI440.4R – Prestressing Concrete Structures with FRP Tendons

ACI 440.1R Flexural Strength Equations

- Design guides are based on limit states design method
- Two ultimate limit states in flexure
  - Reinforcing bar rupture ($\rho_f < \rho_{fbal}$)

$$M_n = [0.8] A_f f_{fu} \left(d - \frac{\beta_1 c_b}{2} \right) \qquad c_b = \frac{\varepsilon_{cu} d}{\varepsilon_{cu} + \varepsilon_{fu}}$$

    - The [0.8] was removed starting with 440.1R-06

  - Concrete crushing ($\rho_f > \rho_{fbal}$)

$$M_n = A_f f_f \left(d - \frac{1}{2} \frac{A_f f_f}{0.85 f_c' b} \right)$$

$$f_f = \sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85 \beta_1 f_c' E_f \varepsilon_{cu}}{\rho_f}} - 0.5 E_f \varepsilon_{cu} \le f_{fu}$$

ACI 440.1R Environmental Service Factors

- Long Term Design Strength Reduction Factor (C_E)
  - Environmental Exposure
    - Tensile Strength Reduction
    - Creep Strength Reduction
    - Fatigue Strength Reduction
- Design/Guaranteed Tensile Strength
  - $f_{fu} = C_E f^*_{fu}$
- Design/Guaranteed Rupture Strain
  - $\varepsilon_{fu} = C_E \varepsilon^*_{fu}$

Exposure Condition	Fiber Type	C_E
Concrete Not Exposed to Earth and Weather	Glass	0.8
	Aramid	0.9
	Carbon	1.0
Concrete Exposed to Earth and Weather	Glass	0.7
	Aramid	0.8
	Carbon	0.9

ACI 440.1R-03 Resistance Factors

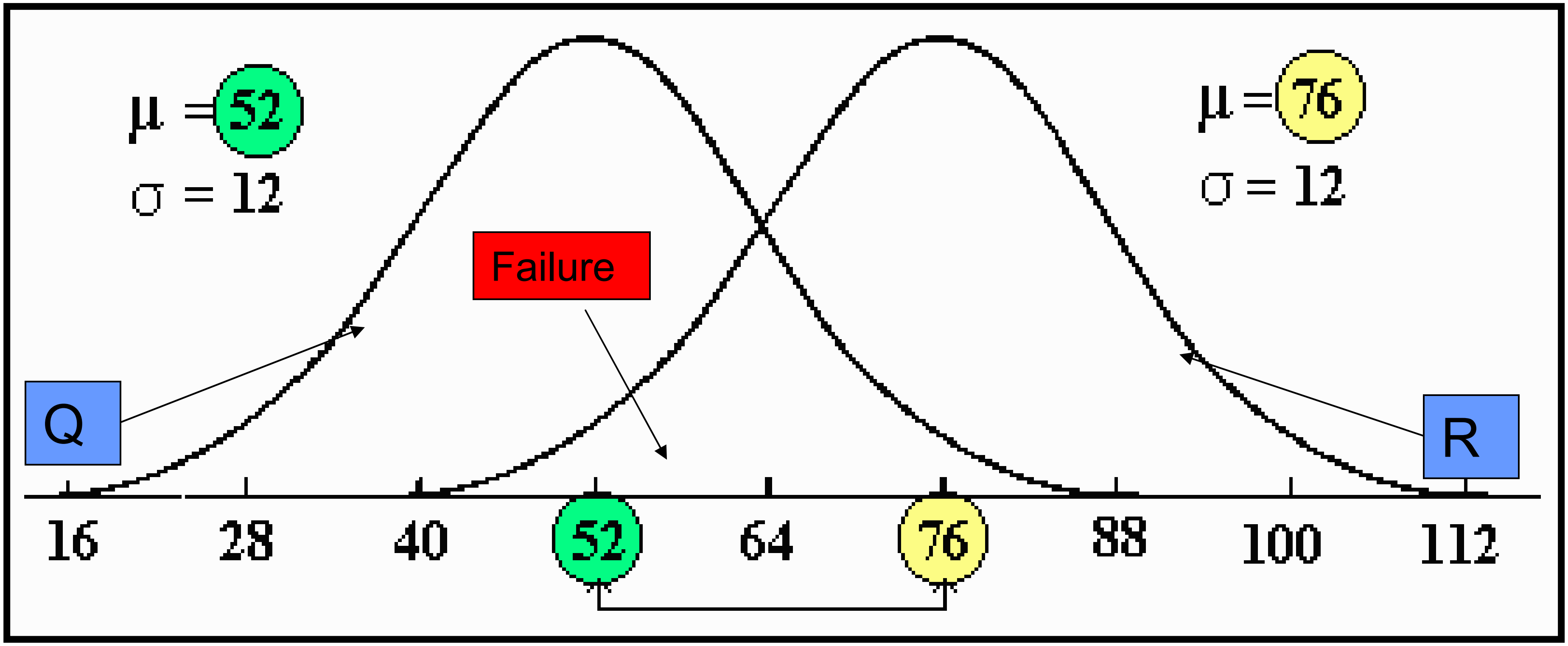
- Load and Resistance Factor Design
  - $\phi M_n \geq M_u$
  - Load factors from ACI 318-99 (i.e. 1.4D+1.7L+…)
- No calibration performed – ϕ based on committee judgement
- Concrete crushing
  - $\phi = 0.7$ for $\rho_f > 1.4\ \rho_{fbal}$
    - Same as ACI318-99 ϕ for failure by concrete crushing prior to steel yielding
- Reinforcement bar rupture
  - $\phi = 0.5$ for $\rho_f \leq \rho_{fbal}$
  - Committee believed that reinforcement bar ruptures were less ductile than concrete crushing failures
- Transition region
  - $\phi = \rho_f / (2\ \rho_{fbal})$ for $\rho_{fbal} < \rho_f < 1.4\ \rho_{fbal}$
  - Original 0.8 in rebar rupture formula caused a discontinuity in M_n at the balanced reinforcement ratio

- R = resistance (limiting capacity)
- Q = load effect (force)
- For structural safety…

$$R \geq Q$$

Reliability Analysis cont…

- R and Q are normally distributed random variable
- Can never achieve 0 probability of failure



Monte Carlo Simulation

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- Estimated Probability of Failure

$$P_f = \frac{N}{n}$$

N = Number of Times Event of Interest Occurred
n = Total Number of Simulations

- Reliability Index

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} = \Phi^{-1}(P_f)$$

  - β=3 → 1/1000
  - β=4 → 3/100,000
  - β=5 → 3/10,000,000

- Typical Target Reliability Indices for R/C → 3-4

Database Characteristics

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- Nine complete references including 62 beams
  - Another 10 references (119 beams) had incomplete information
  - Needed measured f_{fu}, E_f , f_c', b, L, d, and reinforcement size
- 13 aramid, 14 carbon, and 35 glass
- Bar size primarily ≤ No. 5
  - Mainly smaller beams
- Fairly even distribution of failure modes
  - 35 concrete crushing
  - 27 reinforcing bar fractures

Database Characteristics

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- f_{fu} ranging from 500-2070 MPa
- E_f ranging from 41-150 GPa
- Nominal bar diameters ranging from 3 – 19 mm
- Variety of bar surface finishes
- f_c' ranging from 23-76 MPa
- Beam depths raging from 145mm to 510 mm
- Beam width ranging from 90 to 500 mm
- $\rho_f/\rho_{f\,bal}$ ranging from 0.73-2 for observed reinforcement ruptures
- $\rho_f/\rho_{f\,bal}$ ranging from 0.93-16.36 for observed concrete crushing failures

Statistical Parameters

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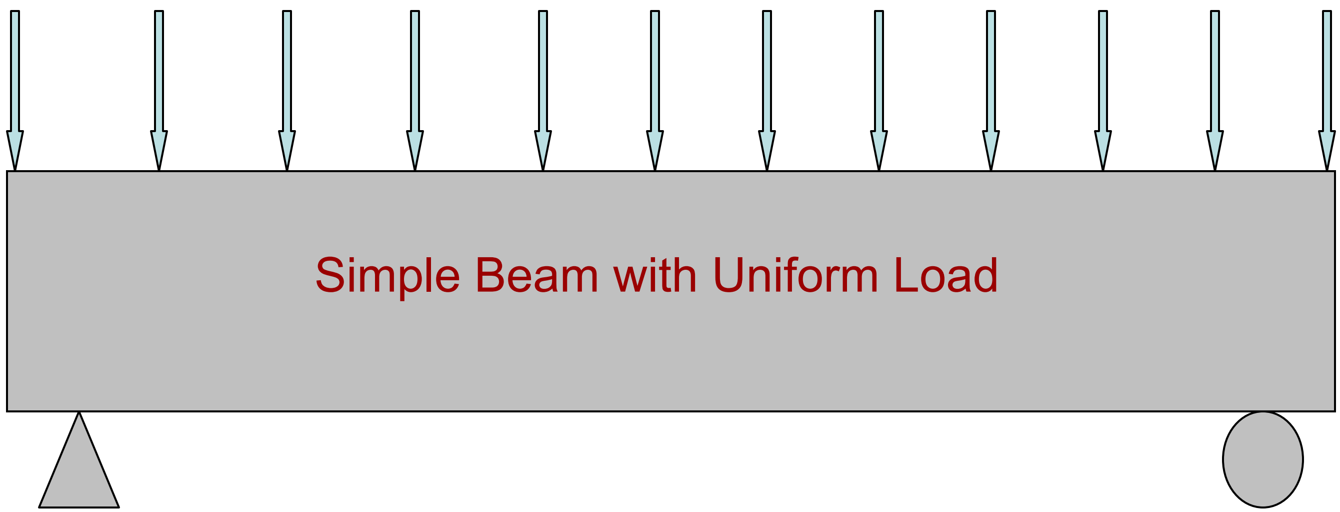
Variable	Bias	Coefficient of Variation	Source
Professional Factor -Rebar rupture failures w/ 0.8	1.11	0.16	Database
Professional Factor -Rebar rupture failures w/o 0.8	0.89	0.16	Database
Professional Factor – Concrete compression failures	1.19	0.16	Database
Area of Reinforcement	1.00	0.03	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#3)	1.18	0.12	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#5)	1.20	0.08	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#6)	1.22	0.07	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#7)	1.12	0.05	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#8)	1.06	0.04	FRP Manufacturer data
Tensile Strength (f_{fu}^*) of GFRP (#9)	1.13	0.05	FRP Manufacturer data
Width of Beam	1.01	0.04	Nowak and Szer szen
Depth of Beam	0.99	0.04	Nowak and Szer szen
Modulus of Elasticity of GFRP	1.04	0.08	FRP Manufacturer data
Concrete Compressive Strength	1.24	0.10	Nowak and Szer szen
Dead Load Moment	1.05	0.10	Nowak and Szer szen
Live Load Moment	1.00	0.18	Nowak and Szer szen

Statistical Parameters Continued…

- Deterministic Variables
  - Environmental Service Factor (C_E)
    - Non-Calibrated Coefficient with Limited Data
  - Ultimate Concrete Compressive Strain (ε_{cu})
    - Considered Deterministic in ACI 318-02
  - Depth of Compression Block (β_1)
    - Considered Deterministic in ACI 318-02

Beam Design Space

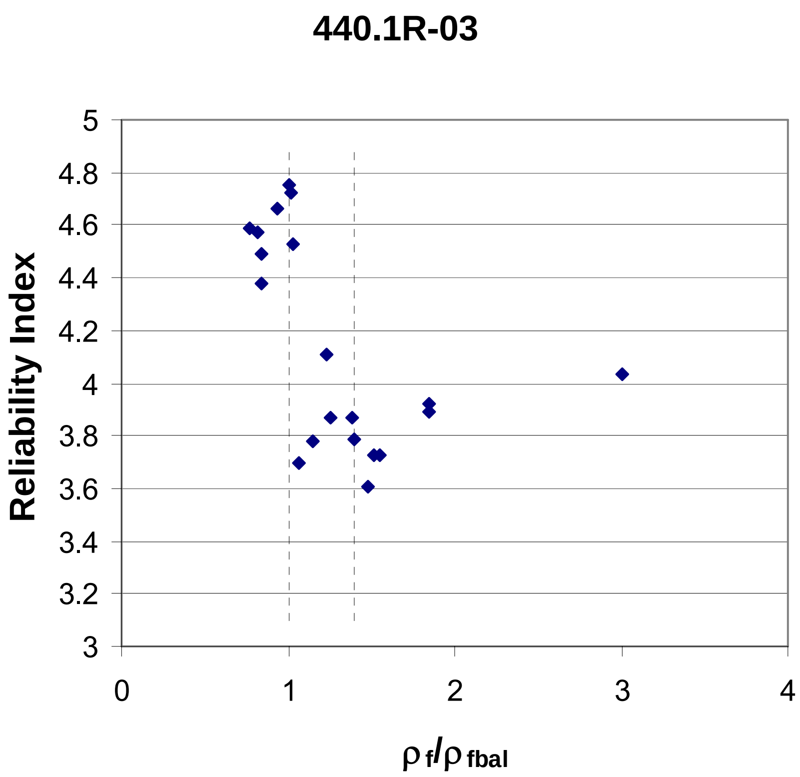
- 20 Design Beams each for 440.1R-03 and 440.1R-06
- Simple Beam Conditions
- Uniform Dead and Live Loads

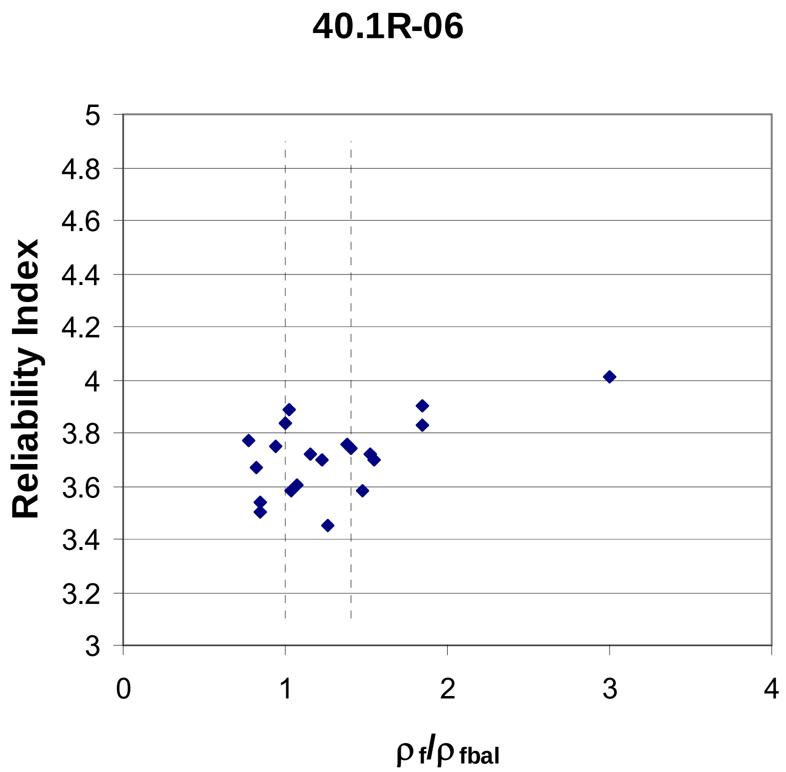


Results

- Required resistance factors for reliability indices between 3.5 and 4 using ACI 440.1R-06 Eqs.
  - Concrete crushing
    - ϕ =0.65 for $\rho_f > 1.4\ \rho_{fbal}$
      - Same as ACI318-02 ϕ for failure "compression controlled" failures
  - Reinforcement bar rupture
    - ϕ=0.55 for $\rho_f \leq \rho_{fbal}$
  - Transition region
    - $\phi = 0.3 + 0.25\rho_f / \rho_{fbal}$ for $\rho_{fbal} < \rho_f < 1.4\ \rho_{fbal}$

Reliability Results





Reinforcement bar rupture more brittle?

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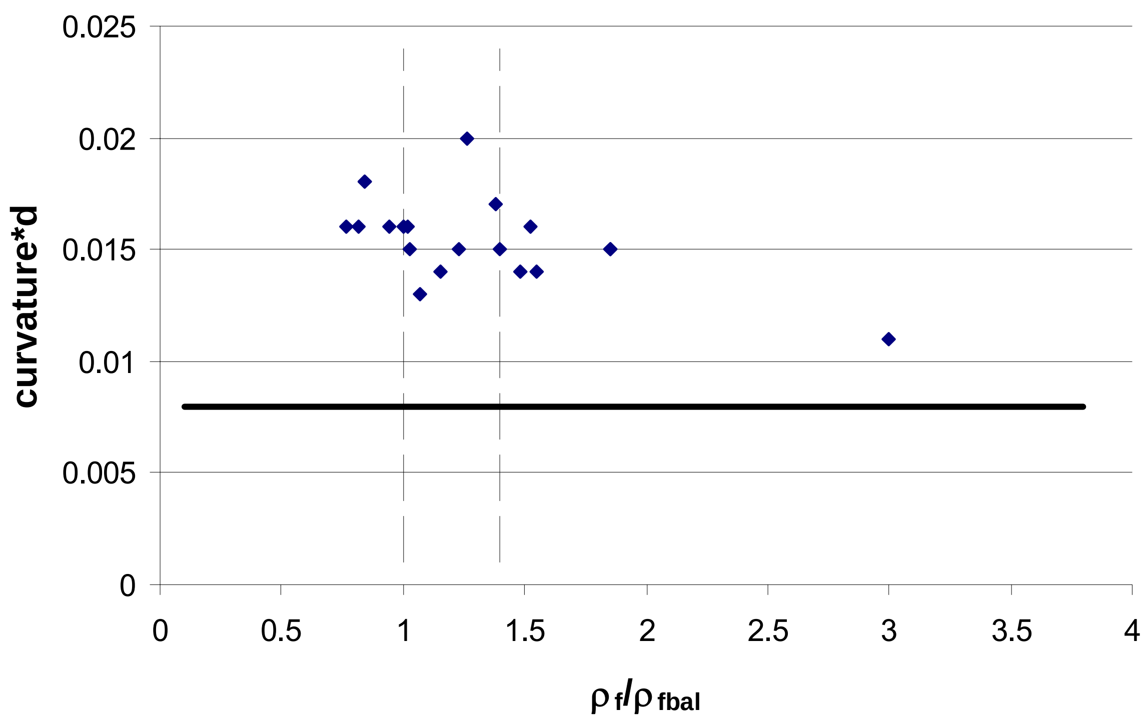
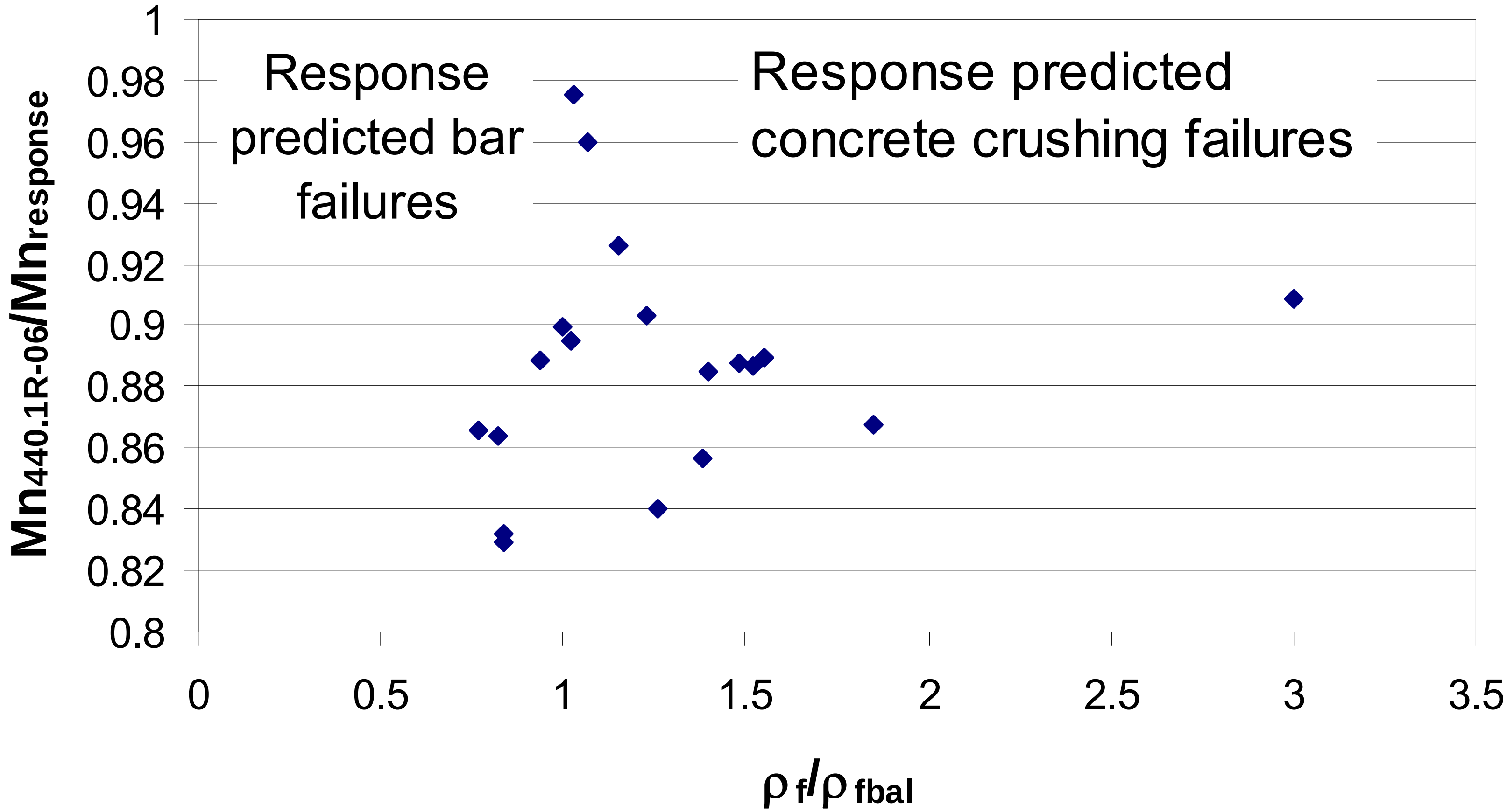
- ACI 318 differentiates between “compression” and “tension” controlled failures by the strain in the steel $\varepsilon > 0.005 \rightarrow$ tension controlled failure
- Convert this into a required curvature
  - $\Phi \geq 0.008/d$



Comparison with nonlinear sectional model



Conclusions

- Reliability of FRP reinforced beams designed with pre ACI440.1R-03 have reliability indices between 3.6 and 4.8
- Reliability indices for ACI440.1R-06 are between 3.45 and 4.01 and less dependant on ρ_f
- Calibrated resistance factors → ~35% reduction in FRP for reinforcement fracture failures
  - Affects initial costs comparisons
- Curvatures of all trial FRP beams were greater than 0.008*d → would have at least as much deflection as steel reinforced beams determined to be "tension controlled" at ultimate
- Similar curvature*d values were obtained for FRP beams failing by FRP rupture as concrete crushing → similar ductilities for the trial beams examined
- ACI440.1R-06 nominal moment capacities are slightly more conservative than those predicted using a strain compatibility analysis with a non-linear material model for the concrete

Where do we go from here?

- Are we using a level playing field?
  - Comparing designs with different material systems only makes sense if they all provide similar reliability (safety)
- Are the populations used to determine reliability indicative of what would be built?
  - Probably not, lots of small beams reinforced with small bars
- Biggest unknown is in environmental factors
  - Currently committee consensus numbers
  - Need good statistical data on these to perform better reliability analysis (WHEN/HOW????)