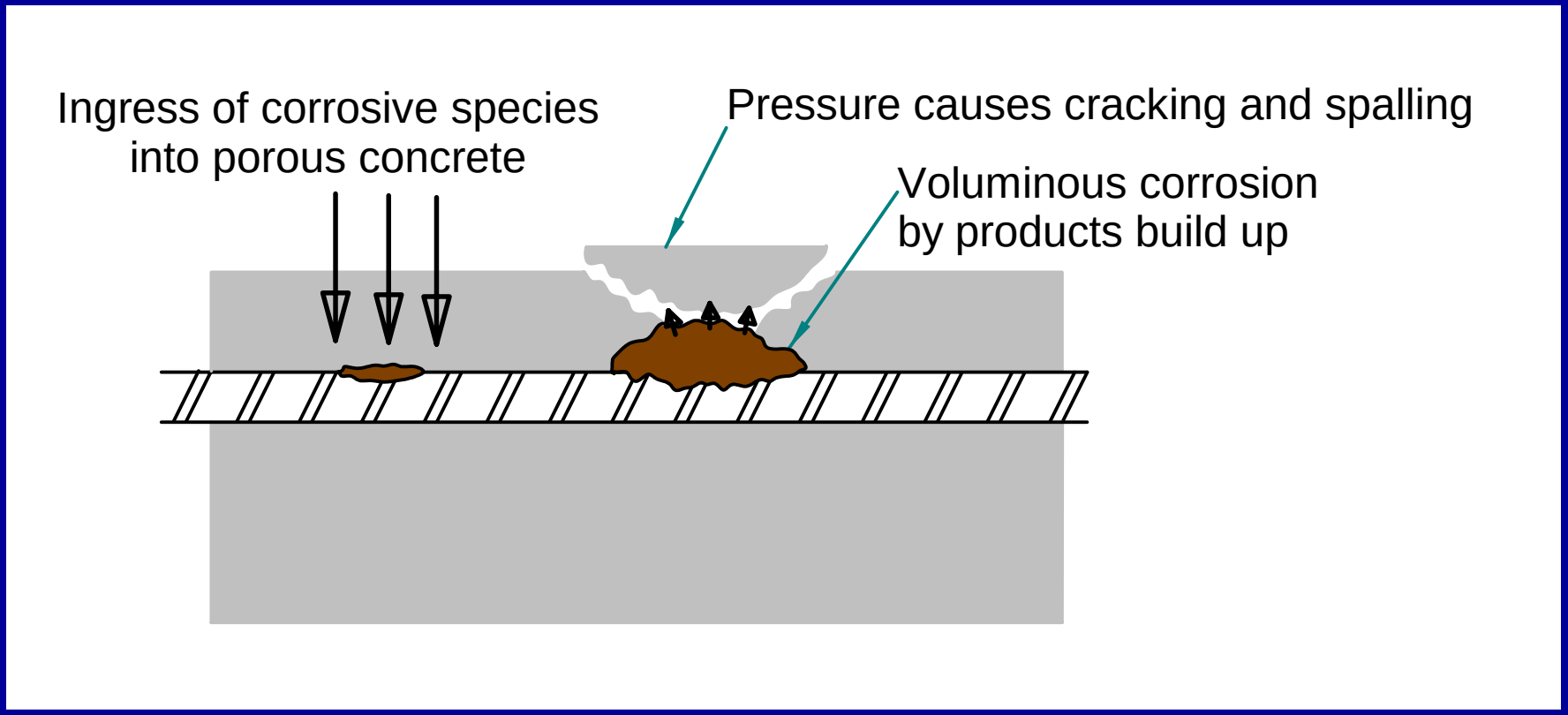
FRP Bars as Internal Reinforcement for Concrete Overview

Carin L. Roberts-Wollmann

Problem with Steel Reinforced Concrete

- Steel reinforcing bars corrode

Corrosion By-Products Cause Spalling



Bridge Deck Degradation

Costly Repairs

Possible Solution: FRP Reinforcing Bars

- Advantages
  - FRP bars do not corrode
  - FRP bars are light weight
  - FRP bars are high strength
- Disadvantages
  - Higher initial cost
  - Lower modulus (particularly GFRP)
  - Strength degradation with time
  - Stress-strain behavior is linear elastic to failure

Presentation Overview

- Material Properties
- Design for Flexure
- Design for Shear
- Others

Design Guidelines

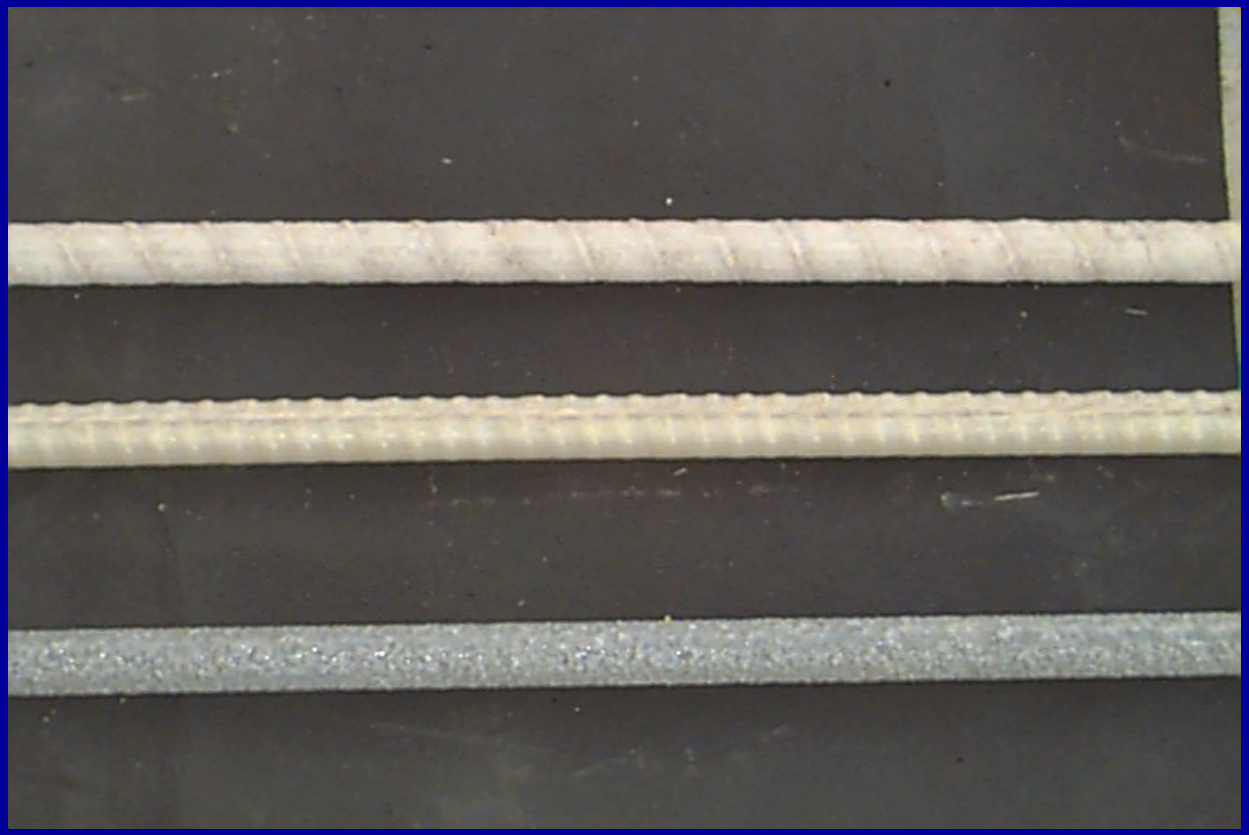
- Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars (ACI 440.1R-06)

Types of FRP Reinforcing Bars

Bar Type	Tensile Strength	Modulus of Elasticity
Steel	60 ksi	29,000 ksi
GFRP	100 ksi	6000 ksi
AFRP	170 ksi	12,000 ksi
CFRP	300 ksi	22,000 ksi

GFRP Most Common

- Least Expensive



GFRP Properties

- Tensile Strength
- Tensile Modulus
- Bond Strength
- Coefficient of Thermal Expansion
- Durability

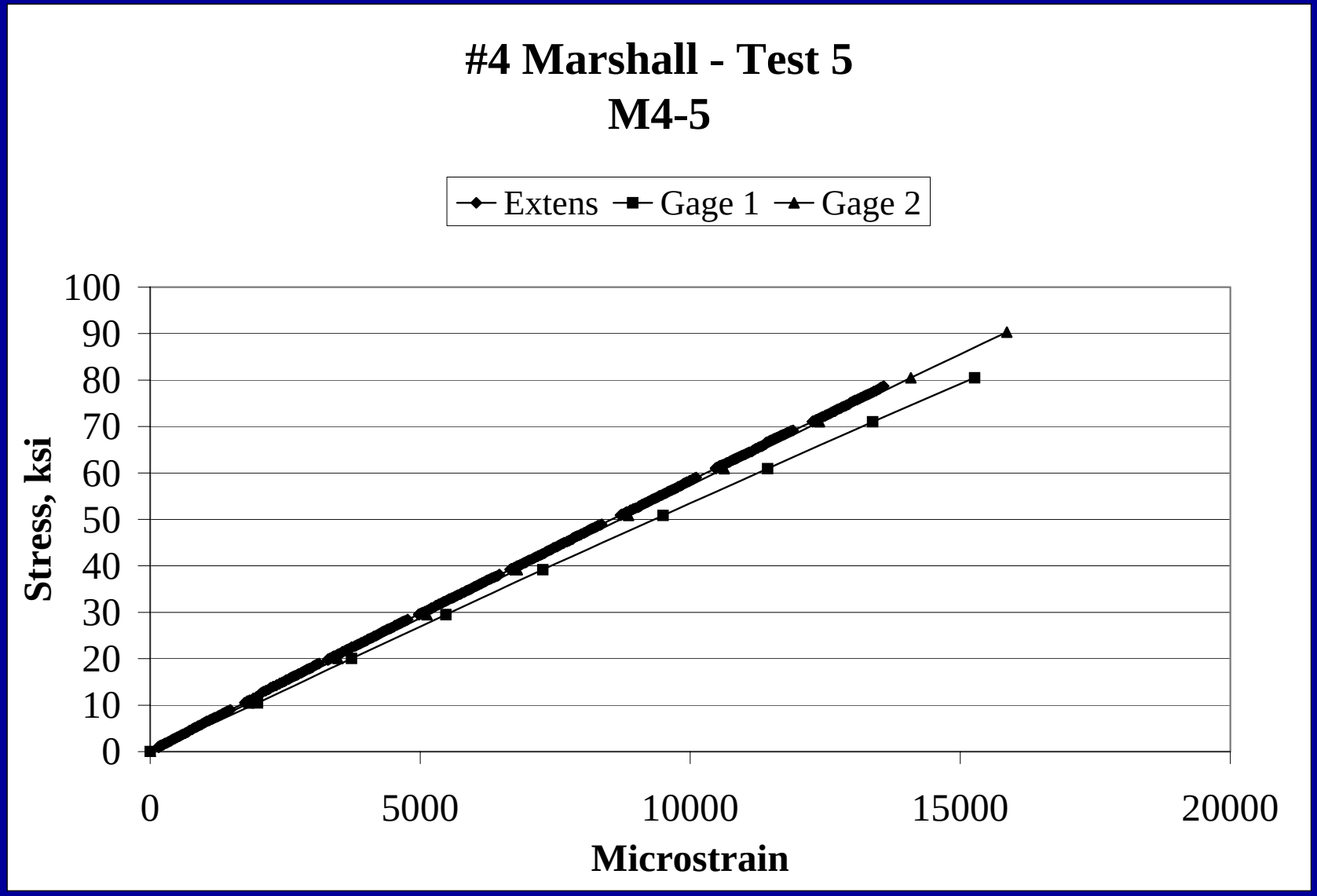
Tensile tests - end anchors

Pipe anchors
Filled with epoxy and sand

Tensile Tests

Machine grips end anchors

Strain measured with clip-on extensometer



Linear elastic until rupture

ACI 440 Definitions and Requirements

- Sample of 5 bars must be tested
- From sample, mean and standard deviation of strength and modulus are determined
- Guaranteed tensile strength is defined as: Mean – 3*Standard Deviation
- Guaranteed modulus is defined as the mean modulus

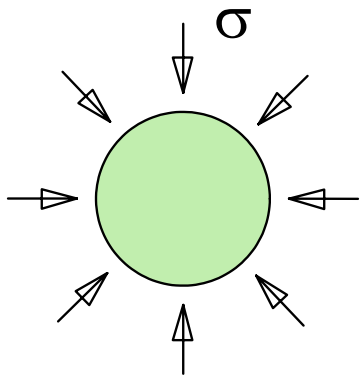
Bond Strength

- Tests have shown bond strength of GFRP bars to be inferior to steel bars
- Manufacturers use a variety of techniques to improve bond
- Current design guideline (ACI 440.1R-06) account for inferior bond in crack width and deflection calculations

Coefficient of Thermal Expansion

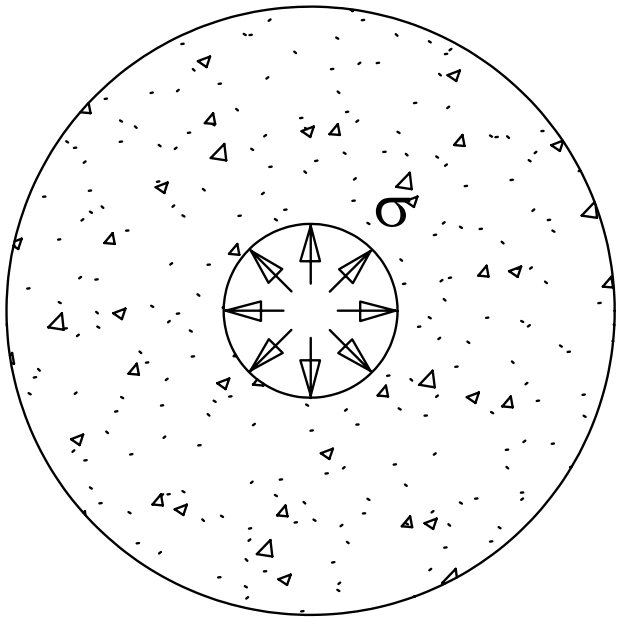
- Concrete 5 to 6 $\mu\varepsilon/°F$
- GFRP longitudinal (dominated by fiber behavior) 3.5 to 6 $\mu\varepsilon/°F$
- GFRP transverse (dominated by polymer) 12 to 25 $\mu\varepsilon/°F$
- Large transverse CTE could cause cracking

Physical Model



Bar

radius = r_b



Concrete Cover

inside radius = $r_c = r_b$

outside radius = r_o

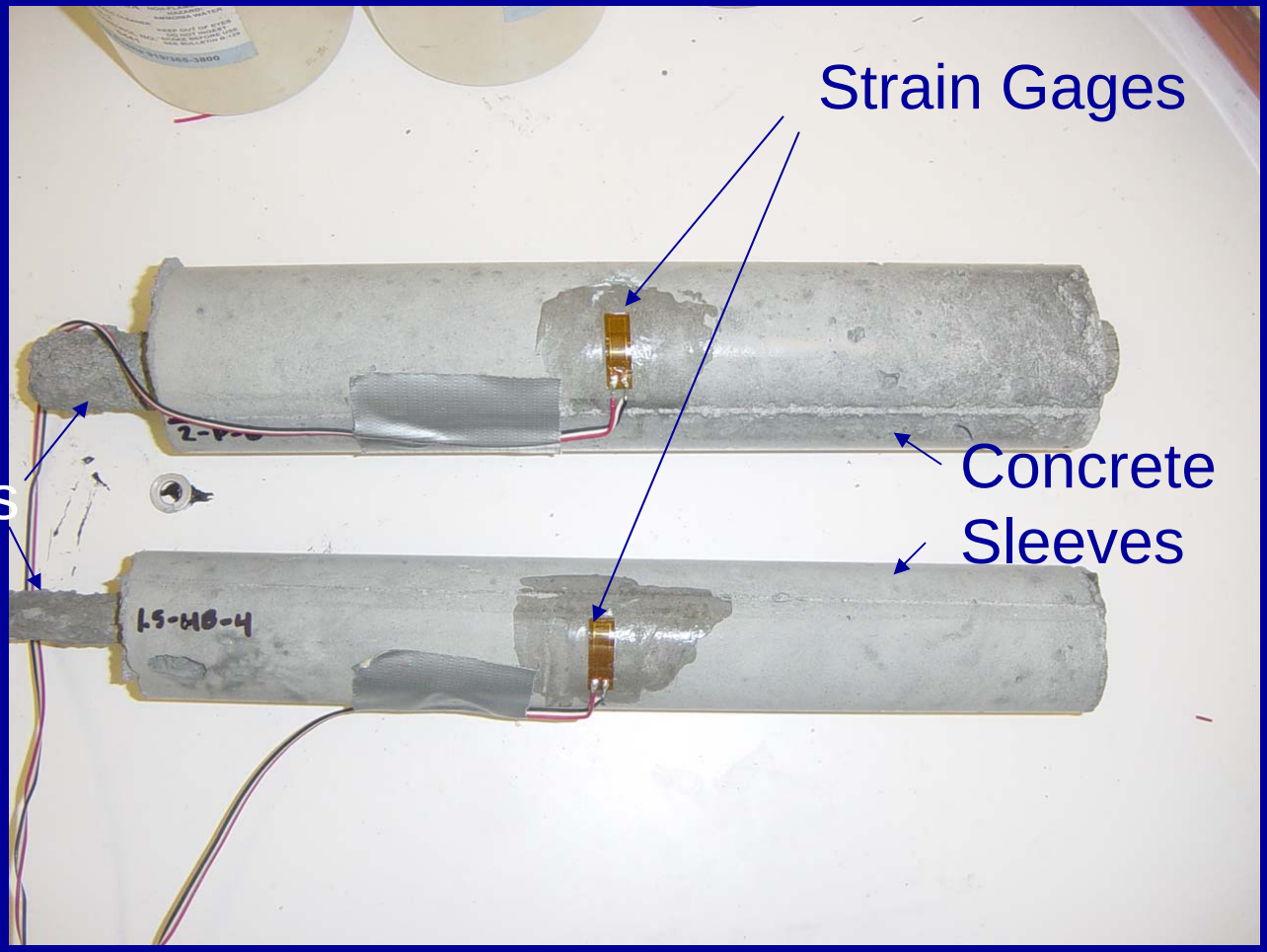
Formulas for Change in Radius

$$\Delta r_b = \alpha_b r_b \Delta T - r_b \frac{\sigma}{E_{tb}}\left(1 - \nu_{tb}\right)$$

$$\Delta r_c = \frac{r_b \sigma}{E_c}\left(\frac{r_o^2 + r_b^2}{r_o^2 - r_b^2} + \nu_c\right) + \alpha_c r_b \Delta T$$

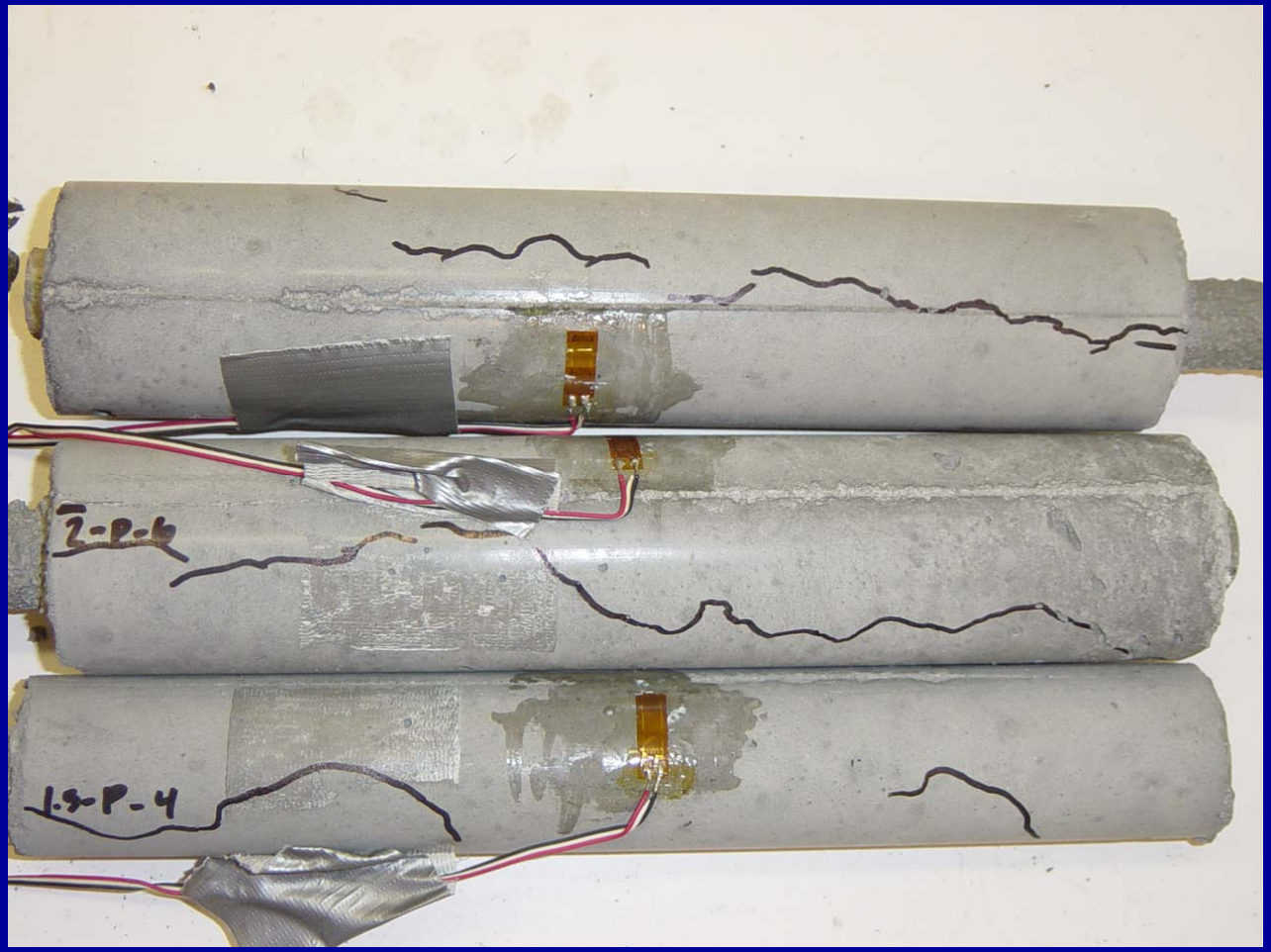
Solve for stress for any change in temperature
Solve for tangential stress associated with radial stress
When tangential stress equals modulus of rupture of concrete, cracking will occur

Test Program



Specimens Placed in Oven

Cracking At High Temperatures



Required Cover

- For typical range of temperatures in bridge decks: 1.5 times bar diameter is adequate cover to prevent cracking

Durability

- GFRP bars experience a reduction in strength over time in moist and alkaline environments such as concrete
- ACI 440.1R-06 recommends the use of an “Environmental Degradation Factor” multiplied by the guaranteed tensile strength to reflect bar strength at end of service life of structure

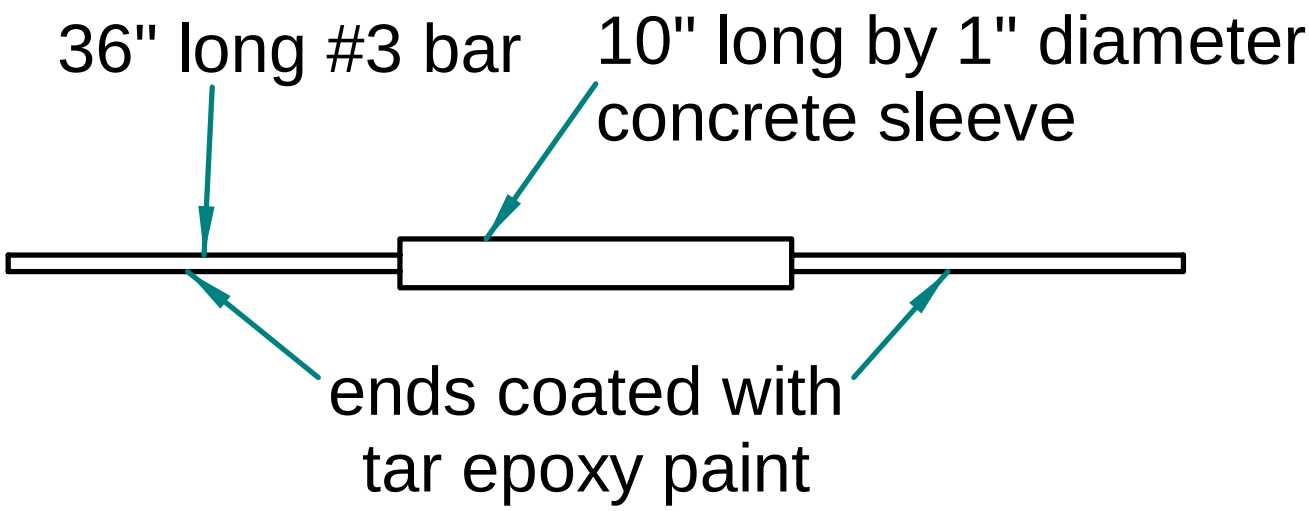
ACI Environmental Reduction Factor (C_E)

Exposure Condition	Fiber Type	C_E
Concrete not exposed to earth and weather	Carbon	1.0
	Glass	0.8
	Aramid	0.9
Concrete not exposed to earth and weather	Carbon	0.9
	Glass	0.7
	Aramid	0.8

Accelerated Aging Tests

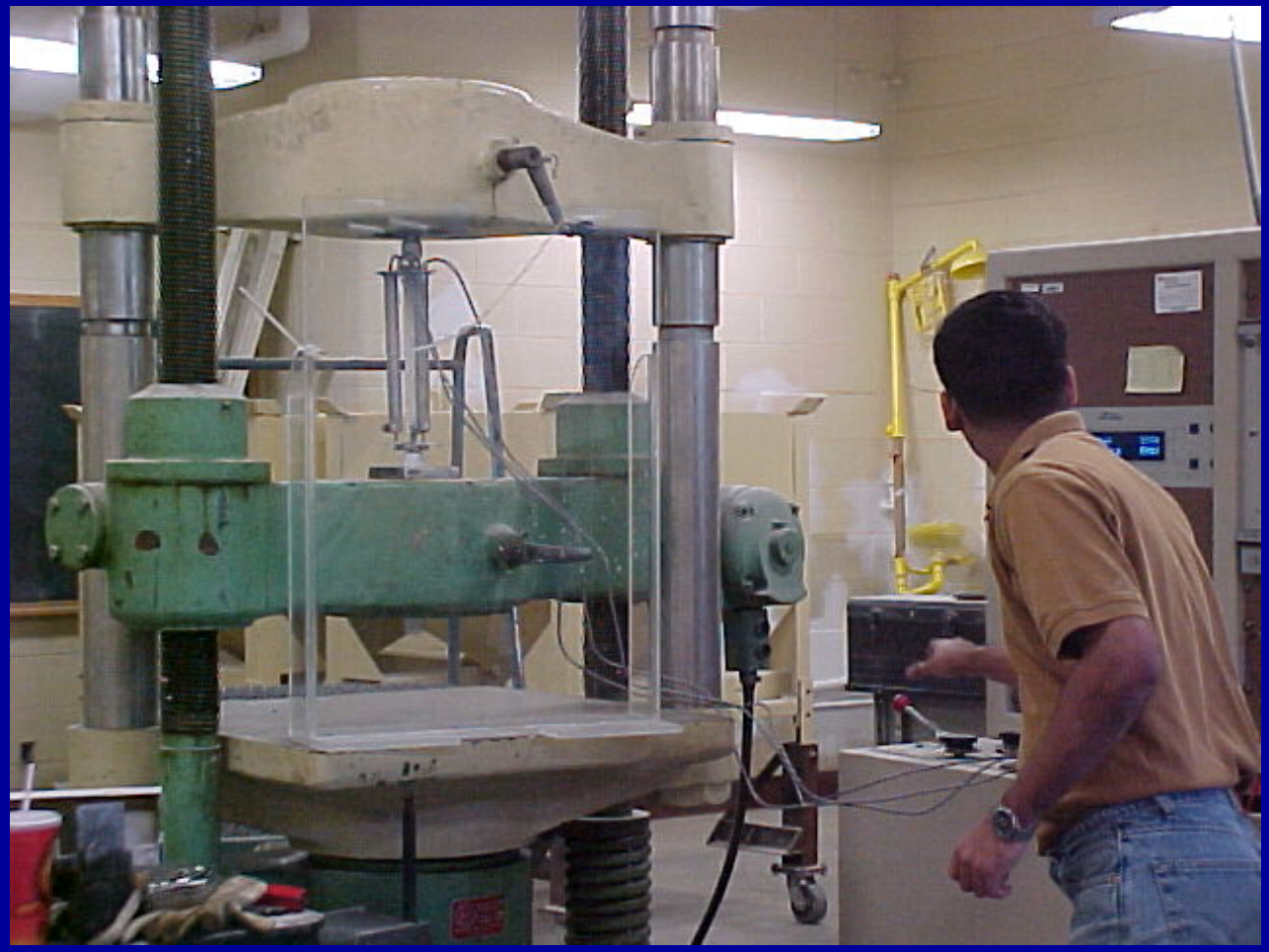
- Assumption is that degradation is caused primarily by a single chemical reaction
- If assumption is correct, then rate of reaction can be increased by increasing temperature
- Specimens are “aged” by placing them in water baths at an elevated temperature

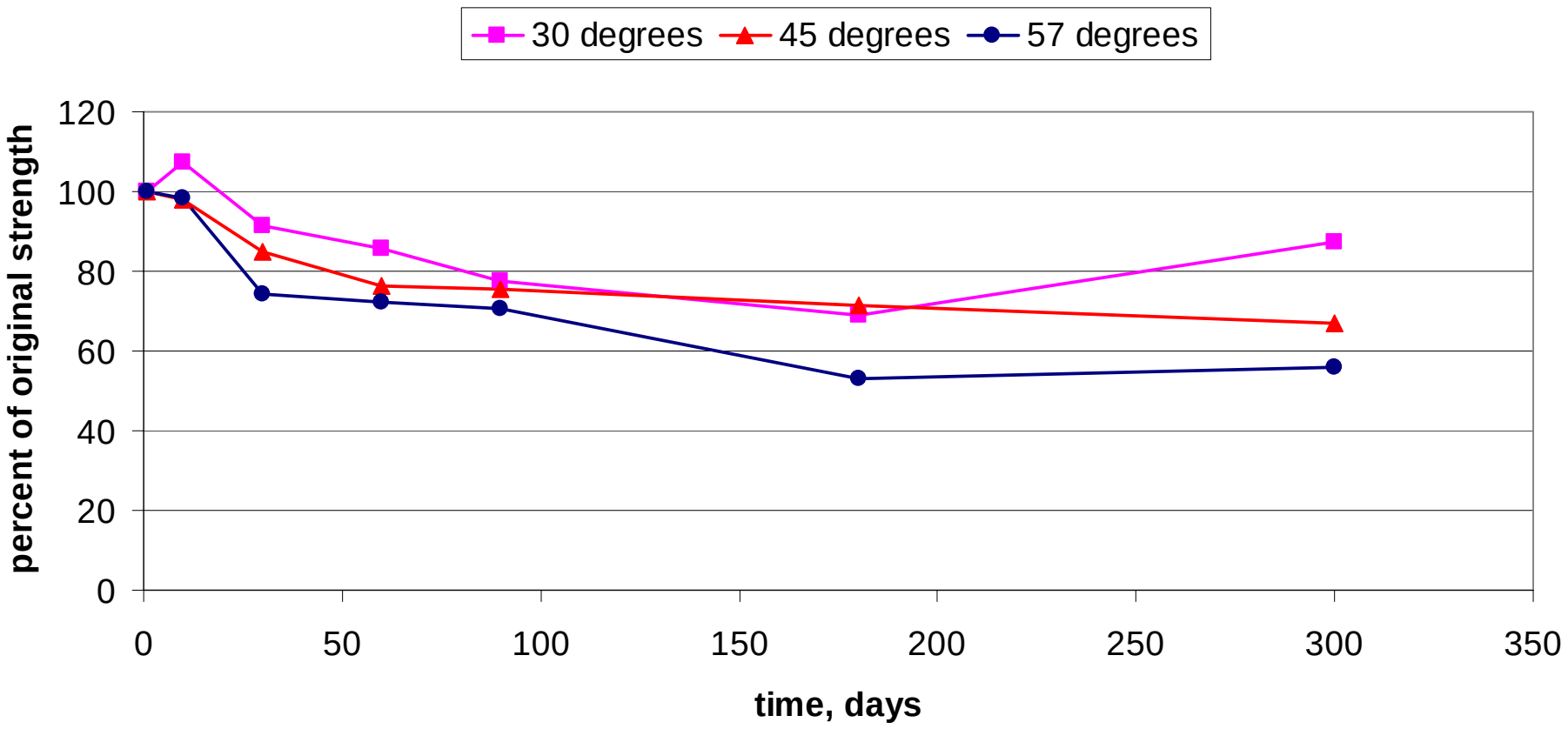
Prepared Specimens



Temperature Baths

Tensile Tests at Regular Intervals



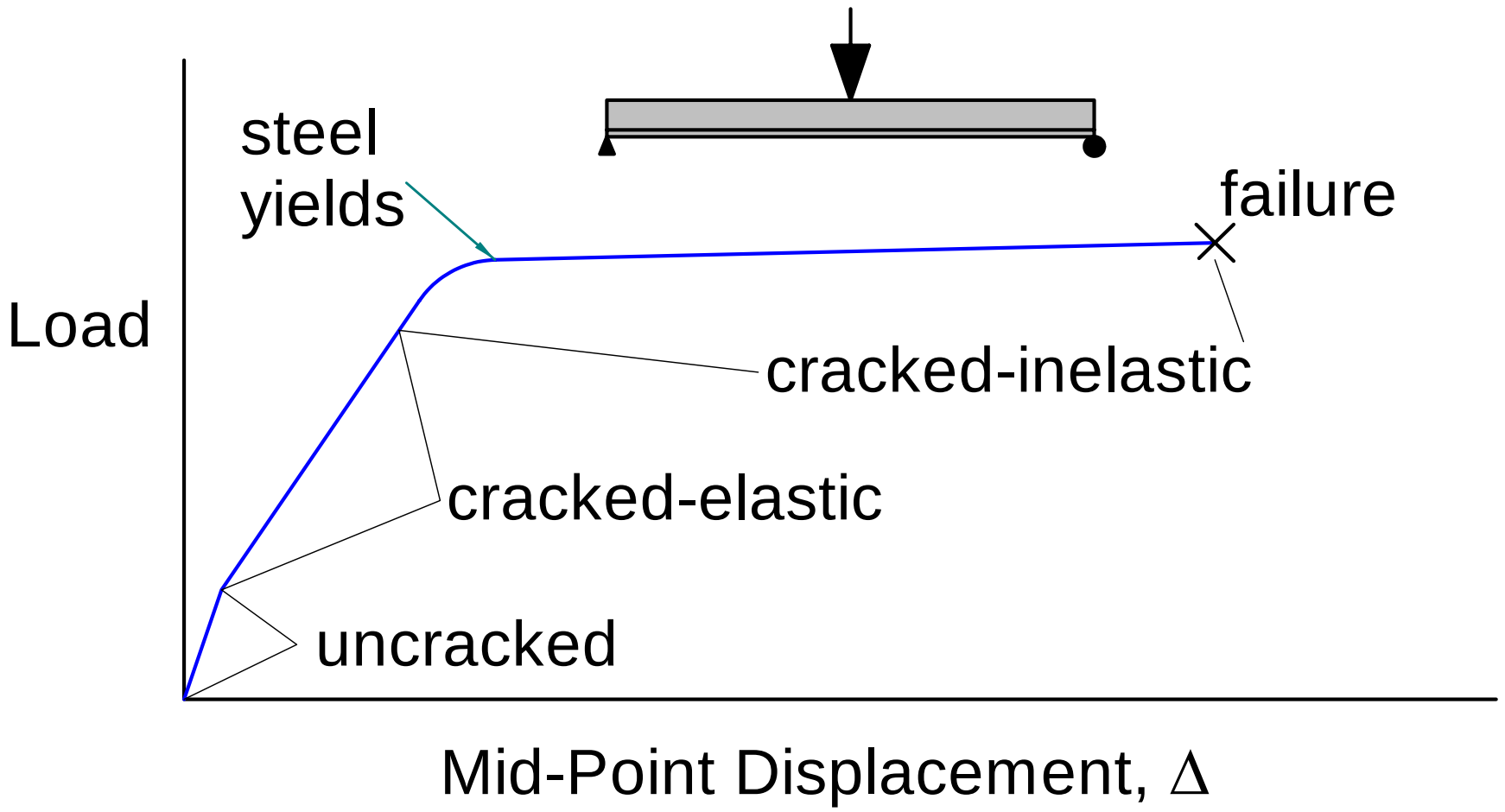

Retained Strength of Conditioned GFRP Bars
30 degrees
45 degrees
57 degrees
percent of original strength
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
time, days

Methods to Analyze Data

- Arrhenius Analysis
- Time Shift Method
- Moisture Content Method

For same data,
each will give a different answer to question:
What is retained strength at end of service?

Reinforced Concrete Behavior



Failure Categories

- Tension controlled - under-reinforced – steel yields before concrete crushes - ductile
- Compression Controlled – over-reinforced- concrete crushed before steel yields – brittle
- Balanced – concrete crushes simultaneously with steel yield - brittle

ACI 318 Design Requirements

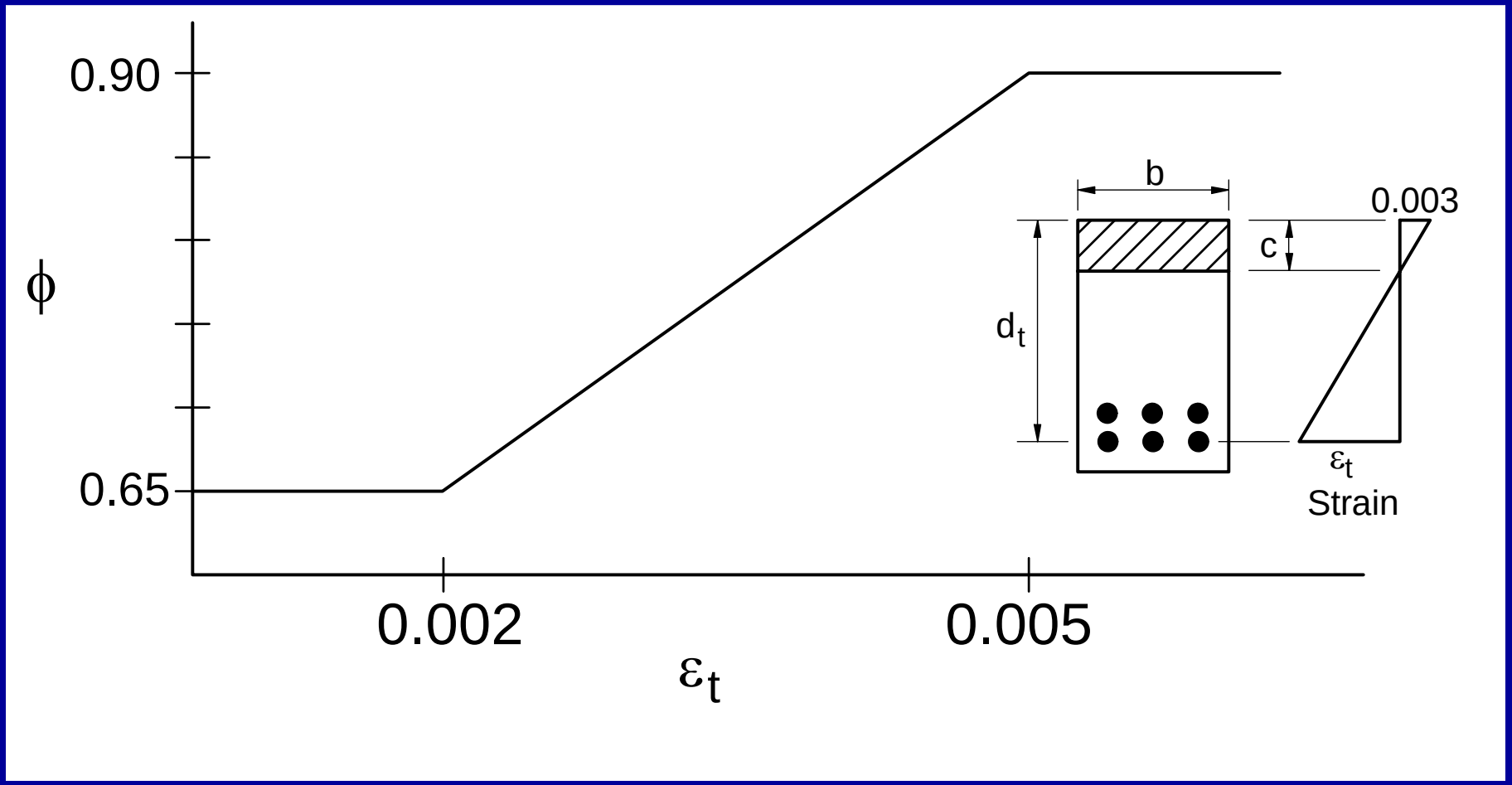
$$M_u \leq \phi M_n$$

M_u = factored moment – based on applied loads times load factors

M_n = nominal flexural strength

ϕ = strength reduction factor

Strength Reduction Factors



Flexural Design with FRP

- No yield plateau for FRP
- Tension controlled and compression controlled are both brittle failures

Determine Failure Mode

Balanced Reinforcement Ratio

$$\rho_{fb} = 0.85\beta_1 \frac{f'_c}{f_{fu}} \frac{E_f \varepsilon_{cu}}{\left(E_f \varepsilon_{cu} + f_{fu}\right)}$$

Over-Reinforced Beam

- Concrete Crushes before Bar Ruptures
- Analyze exactly like over-reinforced beam with steel reinforcement
  - Write expression for strain in reinforcing in terms of depth to neutral axis, c
  - Write equation of internal equilibrium
  - Solve for c
  - Calculate flexural strength

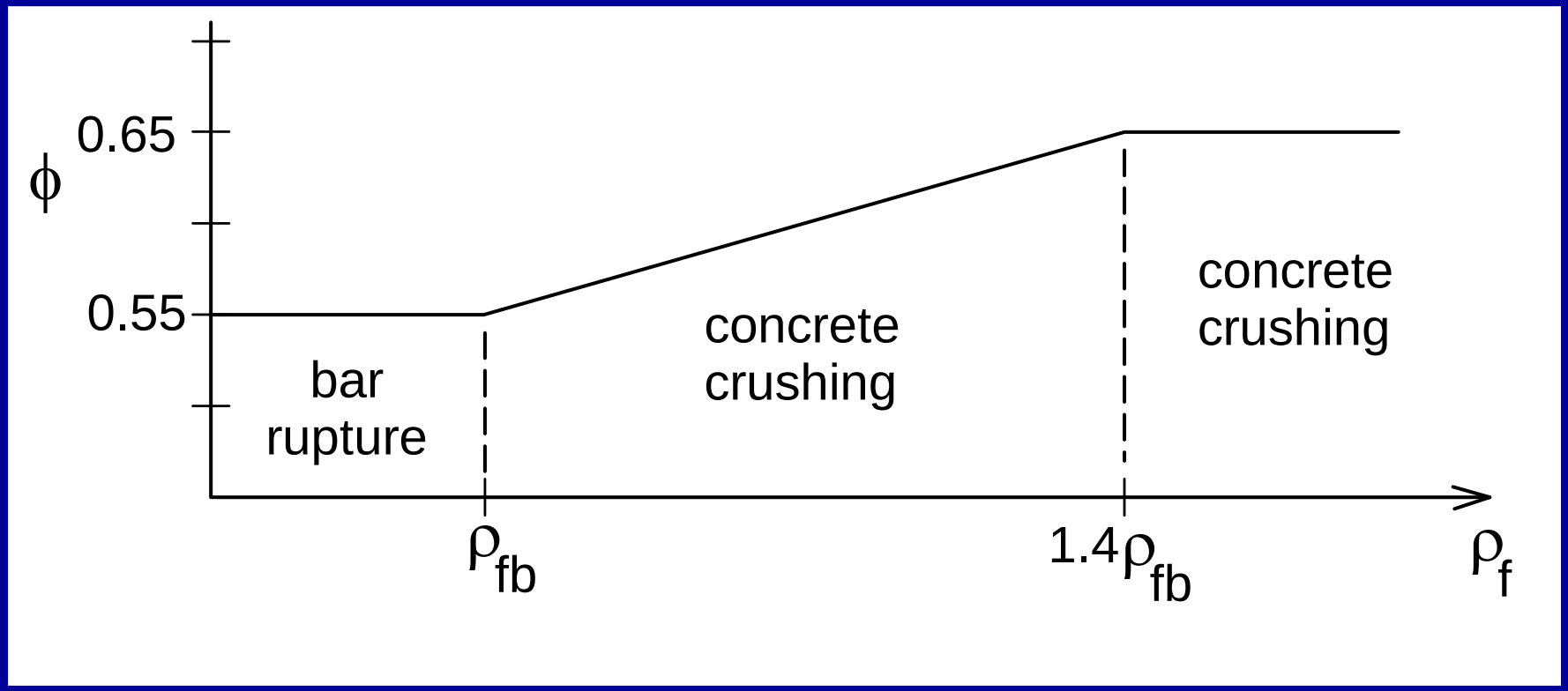
Under-Reinforced Beam

- Bar ruptures before concrete crushes
- Cannot use Whitney stress block
- Parametric studies have shown that a decent approximation is:

$$M_n = A_f f_{fu}\left(d - \frac{\beta_1 c_b}{2}\right)$$

Where c_b is the neutral axis depth for a balanced cross-section

Strength Reduction Factor



Serviceability Checks

- Crack Widths
- Deflections
- Allowable Stresses

Crack Widths

- Similar to ACI spacing requirement, but includes factor to account for lower bond strength

$$w = 2\frac{f_f}{E_f}\beta k_b\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2}$$

Where k_b = bond coefficient

Deflections

- Minimum member thicknesses to prevent excessive deflections
- Direct calculation of deflections

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr}$$

Where β_d = reduction coefficient reflecting reduced tension stiffening

Allowable Stresses

- Calculate with cracked transformed sections at service loads
- Limit stresses to prevent creep rupture and fatigue

Fiber Type	GFRP	AFRP	CFRP
Stress Limit	0.20 f_{fu}	0.30 f_{fu}	0.55 f_{fu}

Shear Strength

- FRP reinforced concrete typically has lower shear strength than steel reinforced concrete of equal flexural strength
- FRP has lower modulus of elasticity so:
  - Cracks open wider and aggregate interlock is reduced
  - Depth to neutral axis based on cracked-elastic behavior is smaller so shear transfer across compression zone is less
- No dowel action

Frosch and Tureyen

- Neglect aggregate interlock
- Assume all shear is transferred across the concrete in compression

$$V_c = 5\sqrt{f'_c}\, b_w c$$

Where c = depth to neutral axis based on cracked transformed section

Shear Strength of FRP Stirrups

- Familiar formula

$$V_f = \frac{A_{fv} f_{fv} d}{s}$$

Other Topics in ACI-440

- Two-way shear strength
- Temperature and shrinkage reinforcement
- Development and splices
- Example problems

Conclusions

- Some fundamental differences between steel reinforced and FRP reinforced concrete
- Well presented in ACI-440.1R-06