Tensile and Shear Capacity of Post-Installed GFRP Bars in Concrete

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Post-Installed Reinforcing Bars

Benefits

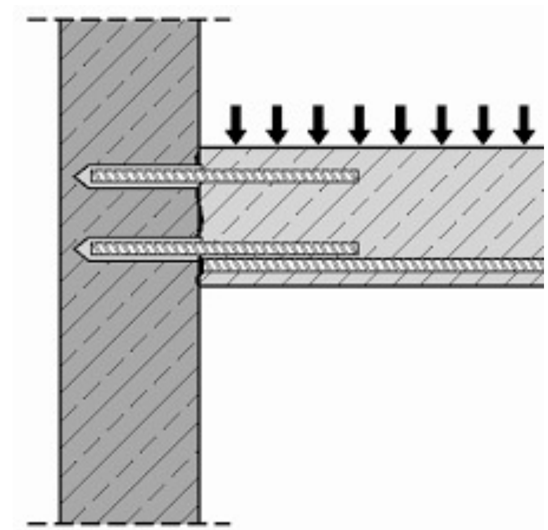
- High design flexibility
- Column extensions, slab-to-slab connections, wall extensions, etc.

ACI 318-19 [1]

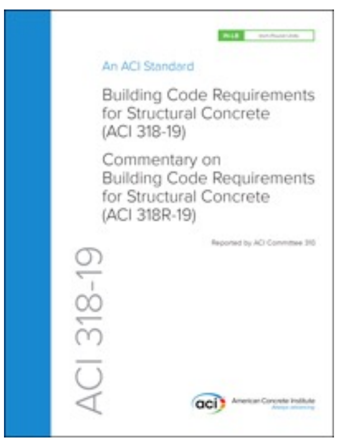
- Ch. 17: Anchoring to Concrete
- Only applicable to steel reinforcing bars

ACI 440.1R-15 [2]

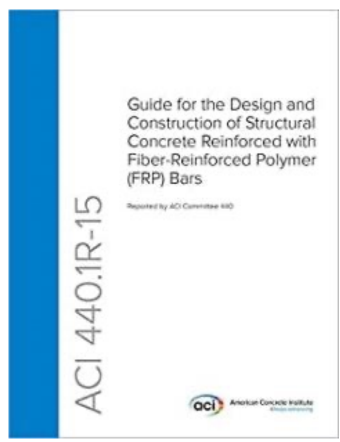
- Basic concrete design using FRP reinforcing bars
- Lack of provisions for anchoring to concrete



Post-installed rebar connection



ACI 318-19



ACI 440.1R-15

Glass Fiber Reinforced Polymer (GFRP)

GFRP Composition

- Fibers: Continuous, carry majority of load
- Resin: Binds and protects fibers

Beneficial properties

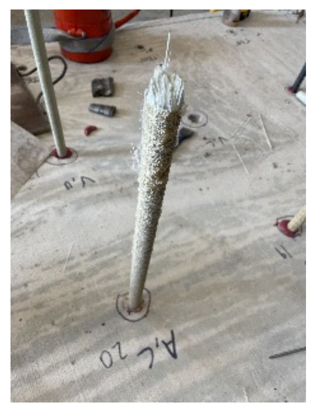
- Higher tensile strength and fatigue resistance compared to steel [2]
- Corrosion resistant, light weight, non-magnetic [2]
- Lowest cost among FRP reinforcing bar types [3]

Uses

- Harsh environments: Bridges, marine structures
- Medical facilities: Non-magnetic nature is useful near MRI machines

Steel and GFRP

GFRP-reinforced bridge deck



GFRP fibers

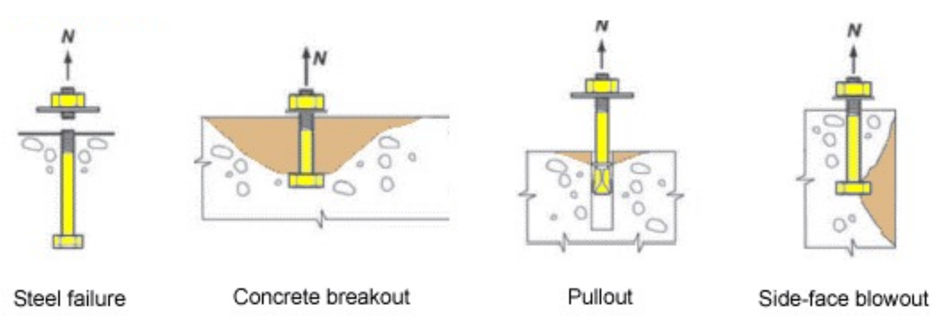
Laboratory Experimental Program

Objectives

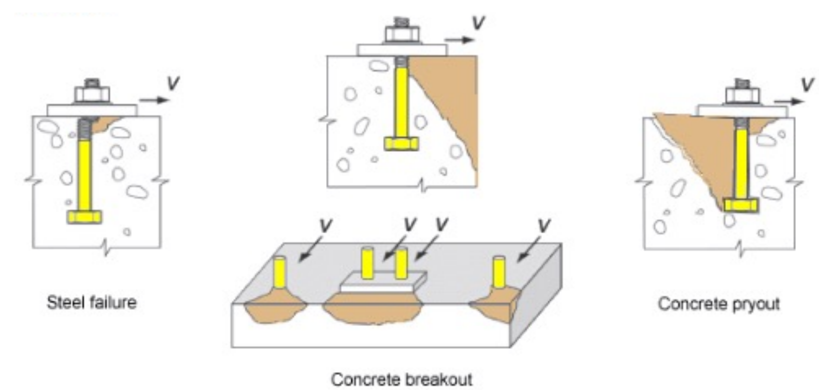
- Determine behavior of post-installed GFRP reinforcing bars subjected to tensile and shear loading
- Determine suitability of ACI 318 provisions to post-installed GFRP reinforcing bars

Laboratory Investigation

- Construct and test specimens with post-installed steel and GFRP reinforcement
- Compare results directly to each other and to predictions made using ACI 318



Tensile failure modes



Shear failure modes

Laboratory Experimental Program

Variables

- Concrete compressive strength (~3500 psi)
- Embedment depth (No. 5 @ 3 in.; No. 8 @ 4 in.)
- Reinforcing bar type (GFRP 1, GFRP 2, Steel)
- Adhesive type (Hilti HIT-RE 500 V3)

ACI 355.3 [4]

- Test 7a: Confined tension away from edges
- Test 7a: Unconfined tension away from edges
- Test 10: Unconfined tension in corner condition
- Test 12: Direct shear strength away from edges

Reinforcing bars tested

Test 7a (C)

Test 7a (U)

Test 10

Test 12

Summary: Laboratory Experimental Program

Test series	Concrete strength (psi)	Embedment depth (in.)	Adhesive type	Bar size	ACI 355.4 test and reference	Reinforcing bars tested	No. tests
1	3500	3	Hilti HIT-RE 500 V3	No. 5	Tension – 7a (Confined)	GFRP 1	5
						GFRP 2	5
						Steel	5
2					Tension – 7a (Unconfined)	GFRP 1	5
						GFRP 2	5
						Steel	5
3					Edge distance -10	GFRP 1	5
						GFRP 2	5
4		4		No. 8	Tension – 7a (Confined)	GFRP 1	5
						GFRP 2	5
						Steel	5
5					Tension – 7a (Unconfined)	GFRP 1	5
						GFRP 2	5
						Steel	5
6		3		No. 5	Shear - 12	GFRP 1	5
						GFRP 2	5
						Steel	5

Results: Statistical Comparisons

Compare Experimental Post-Installed Steel and GFRP Reinforcing Bars

- Ratios of average ultimate loads
- T-Test Analyses (Unequal variance, two-tailed, 5% significance level)
  - GFRP 1 to Steel
  - GFRP 2 to Steel
  - GFRP 1 to GFRP 2

Compare Experimental Post-Installed Steel and GFRP Reinforcing Bars to ACI 318-19 [1] Predicted Capacities

- Delineated by failure mode
- Average ultimate load reduced by three standard deviations (3σ)
  - Incorporates 99% of normal distribution
- Characteristic value (5% fractile)
  - 95% probability of being exceeded, with a confidence of 90%

Results: Confined Tensile Tests

Direct Comparisons

- No. 5 reinforcing bars
  - GFRP 1: Statistically different, lower capacity than steel
  - GFRP 2: Statistically different, lower capacity than steel

- No. 8 reinforcing bars
  - GFRP 1: Not statistically different than steel
  - GFRP 2: Statistically different, lower capacity than steel

Test 7a (C)

Stress concentrations: potential premature failure of GFRP reinforcing bars due to anchor rupture at point of anchorage

GFRP anchor rupture

Results: Confined Tensile Tests

Comparisons to ACI 318 [1] Predicted Capacities

Reinforcing Bar	Failure mode	Ratio of average ultimate load reduced by 3σ to ACI predicted capacity	Ratio of characteristic value to ACI predicted capacity
GFRP 1	Bond	No. 5 - 2.43	No. 5 – 2.36
		No. 8 – Insufficient SS	No. 8 – Insufficient SS
	Anchor Rupture	No. 5 – Insufficient SS	No. 5 – Insufficient SS
		No. 8 – 0.87	No. 8 – 0.75
GFRP 2	Bond	No. 5 - Insufficient SS	No. 5 – Insufficient SS
		No. 8 – Insufficient SS	No. 8 – Insufficient SS
	Anchor Rupture	No. 5 - 0.93	No. 5 – 0.89
		No. 8 – 0.46	No. 8 – 0.41
Steel	Bond	No. 5 - 2.26	No. 5 – 2.12
		No. 8 – 2.54	No. 8 – 2.46

(Green) Indicates ratio > 1.0

Insufficient SS = Insufficient sample size for statistical comparisons

Results: Unconfined Tensile Tests

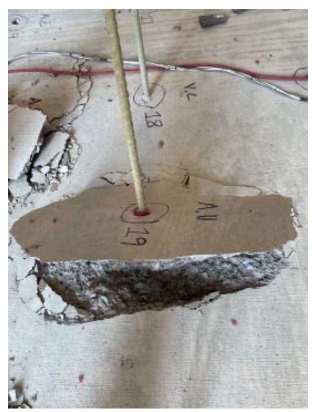
Direct Comparisons

- No. 5 reinforcing bars
  - GFRP 1: Not statistically different than steel
  - GFRP 2: Not statistically different than steel

- No. 8 reinforcing bars
  - GFRP 1: Not statistically different than steel
  - GFRP 2: Not statistically different than steel

Test 7a (U)

Concrete strength: Influencing factor on unconfined tensile strength



Concrete breakout

Results: Unconfined Tensile Tests

Comparisons to ACI 318 [1] Predicted Capacities

Reinforcing Bar	Failure mode	Ratio of average ultimate load reduced by 3σ to ACI predicted capacity	Ratio of characteristic value to ACI predicted capacity
GFRP 1	Concrete breakout	No. 5 – 1.49	No. 5 – 1.38
		No. 8 – 1.75	No. 8 – 1.66
GFRP 2	Concrete breakout	No. 5 – 1.75	No. 5 – 1.66
		No. 8 – 1.92	No. 8 – 1.85
Steel	Concrete breakout	No. 5 – 1.63	No. 5 – 1.54
		No. 8 – 2.11	No. 8 – 2.07

(green) Indicates ratio > 1.0

Results: Shear Tests

Direct Comparisons

- No. 5 reinforcing bars
  - GFRP 1: Statistically different, lower capacity than steel
  - GFRP 2: Statistically different, lower capacity than steel

Test 12

GFRP lacks fibers oriented transversely, known to be weak in shear

Typical shear failure in GFRP bar

Typical shear failure in concrete with steel bar

Results: Shear Tests

Comparisons to ACI 318 [1] Predicted Capacities

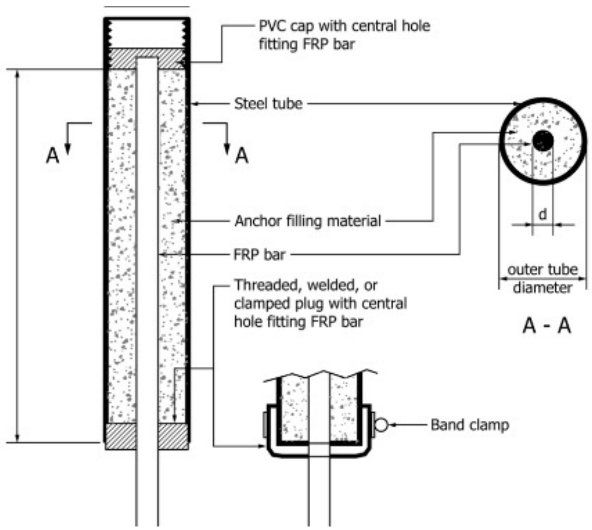
Reinforcing Bar	**Failure mode**	**Ratio of average ultimate load reduced by 3σ to ACI predicted capacity**	**Ratio of characteristic value to ACI predicted capacity**
GFRP 1	Anchor rupture	No. 5 – 0.22	No. 5 – 0.19
GFRP 2	Anchor rupture	No. 5 – 0.32	No. 5 – 0.30
Steel	Concrete breakout	No. 5 – 0.72	No. 5 – 0.66

Recommendations

- Limit stress concentrations around points of anchorage
  - e.g., rigid pipe-shaped anchor as interface between reinforcing bar and grip

- Expand testing variables and parameters
  - Additional types of tests in both cracked and uncracked concrete
  - More reinforcing bar sizes
  - More GFRP reinforcing bar manufacturers
  - Different adhesive types
  - Varied embedment depths
  - Varied concrete compressive strengths

- Explore variations in tensile and shear strength related to varied design guidelines in ACI 440.1R



Rigid pipe-shaped anchor

Questions?

Thank you!

Sources

[1] ACI Committee 318. (2019). *Building Code Requirement for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*. Farmington Hills, MI.

[2] ACI Committee 440. (2015). *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars (ACI 440.1R-15)*. Farmington Hills, MI.

[3] Mertz, D. R. (2003). Application of Fiber Reinforced Polymer (FRP) Composites to the Highway Infrastructure: Strategic Plan. In *Report 503*.