Review and Analysis of FRP Bond Lengths from Pull-out Testing Database with Reduced Embedment Lengths

John J. Myers, Ph.D., P.E., F.ACI, F.IIFC, F.ASCE, F.IAAM, F.TMS, F.VEST

March 23rd, 2024

Welcome to FRPRCS 16
from the Conference Chairs

Ayman M. Okeil

Pedram Sadeghian

John J. Myers

Maria D. Lopez

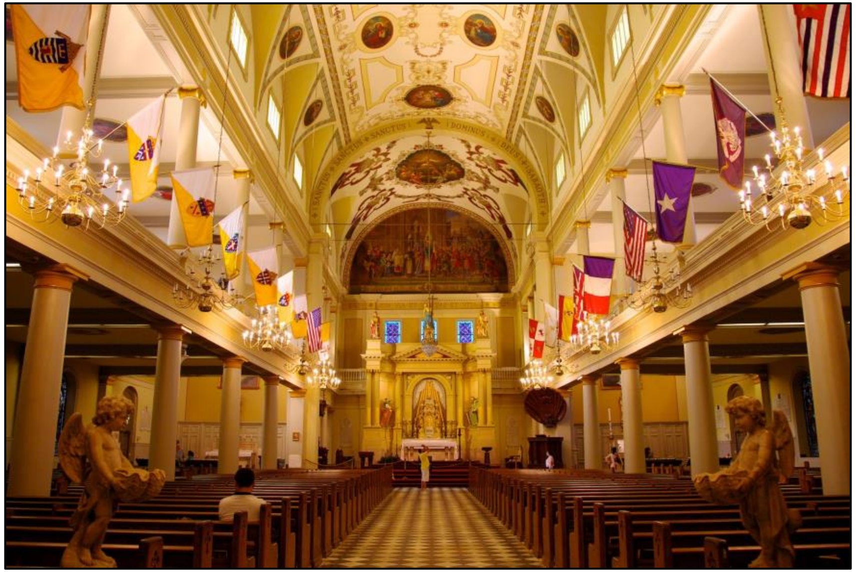
NEX FYFE ACMA MST BAR SIMPSON Strong-Tie MCTI Missouri S&T MODJESKI and MASTERS IIFC International Institute for FRP in Construction

THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci CONCRETE CONVENTION

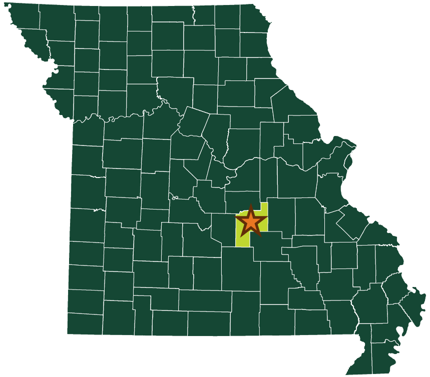
Welcome to FRPRCS 16

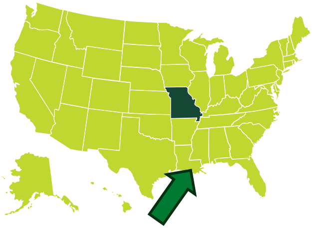
Thanks to ACI and IIFC for Conference Support and to **Maria**, **Ayman** and **Pedram** as Co-Chair Team members!



About Missouri S&T

Where are we located?





- Founded in 1870
- Oldest STEM Campus West of Mississippi River
- Major new investments in ACML, Innovation Lab, Welcome District, Advanced Manufacturing Protoplex

About Missouri S&T

Facts about Missouri S&T CEC

17 undergraduate degree programs.

3775 undergraduate students on campus.

Engineering accounts for **77.7%** of total undergraduate enrollment at S&T.

329 MS students on campus; **386 PhD** students on campus; 427 Extended learning students.

128 Tenured and tenure track faculty members.

38 Non-tenure track faculty members (28 teaching; 10 research).

51 faculty with endowed professorships or named teaching fellowships.

$249,500 per tenured or tenure track faculty.

About MCTI – Missouri Center for Transportation Innovation

Missouri's Statewide Transportation Center

- **Grand Opening** in **Dec. 1999**
- A partnership between the **University of Missouri System** and **MoDOT**, in cooperation with **FHWA**, other universities and the transportation community at large.

MCTI
MISSOURI CENTER FOR
TRANSPORTATION
INNOVATION
PROPELLING PEOPLE · CONNECTING COMMUNITIES · ENERGIZING ECONOMIES

UMKC MoDOT MISSOURI S&T UMSL

CENTER GOALS: CONDUCT & DISSEMINATE PRACTICAL, TIMELY AND IMPLEMENTABLE INNOVATIVE RESEARCH; INCREASE MISSOURI'S PARTICIPATION AND INFLUENCE IN **NATIONAL RESEARCH**; PRODUCE **FUTURE TRANSPORTATION ENGINEERS**; CREATE AN ATMOSPHERE THAT **DEVELOPS FACULTY AND STAFF** AT THE UNIVERSITY AND MODOT.

Propel People…Connect their Communities…and Energize their Economies

FRPRCS 16

Missouri University of Science and Technology

Review and Analysis of FRP Bond Lengths from Pull-out Testing Database with Reduced Embedment Lengths

John J. Myers, Ph.D., P.E., F.ACI, F.ASCE, F.IAAM, F.IIFC, F.VEST, F.TMS

March 23, 2024

MISSOURI CENTER FOR TRANSPORTATION INNOVATION

PROPELLING PEOPLE · CONNECTING COMMUNITIES · ENERGIZING ECONOMIES

Motivation for Investigation

FRP Bar Bond Behavior

A Review and Analysis of Reduced FRP Bonded Bars in Reinforced Concrete (RC)

- The **American Concrete Institute (ACI) 440.1R-15** *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars* **linearly reduces the bar stress** and **thereby pull-out capacity of GFRP bars to zero from an embedment length at 20 bar diameters (d_b) or less**.
- Most experimental research and data **examine the development length of various FRP bars at longer, more traditional, embedment lengths**.

Motivation for Investigation

FRP Bar Bond Behavior

A Review and Analysis of Reduced FRP Bonded Bars in Reinforced Concrete (RC)

- This investigation examines the **bond performance of short embedded FRP bars into concrete** considering a pull-out failure mode to **expand the understanding of short embedded FRP bars into concrete**.
- What about epoxy **embedded FRP dowels** into reinforced concrete?

Presentation Outline

Part A---Introduction and Background

- a.---Advantages of FRP bars
- b.---What are the bond evaluation test methods?

Part B---Research Investigation

- a.---Details on assembling the data collection from literature
- b.---Bond failure modes and case study
- c.---Formation of the database
- d.---Estimating bar stress and bond performance

Part C---Conclusions and Future Work

- a.---Conclusion
- b.---Future and ongoing work

Background

Reinforcement Corrosion Mechanisms

In the U.S., the **total direct cost of corrosion** is estimated at **$276 billion** per year, which is **3.1%** U.S. gross domestic product (GDP). **Worldwide** the cost is estimated at **$2.5 trillion** or **3.4%** GDP.

Corrosion of **reinforced concrete** (RC) is a major factor contributing to deterioration of structures.

Background

FRP Reinforcement for use in Reinforced Concrete (RC)

Advantages:

- ❑ Non-metallic; therefore, do not corrode.
- ❑ Light-weight material; does not add significant mass.
- ❑ High-strength material; allows for higher tensile capacity.

Limitations:

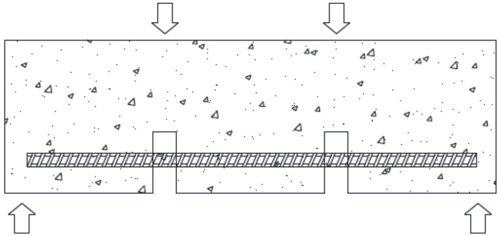
- ❑ Reduced bond performance compared to mild steel.
  - Typically, little or no bond contribution from bearing.
- ❑ Linear elastic, long-term durability (C_E factor) must be considered and use in high temperature applications may cause issues (above T_g).

Background

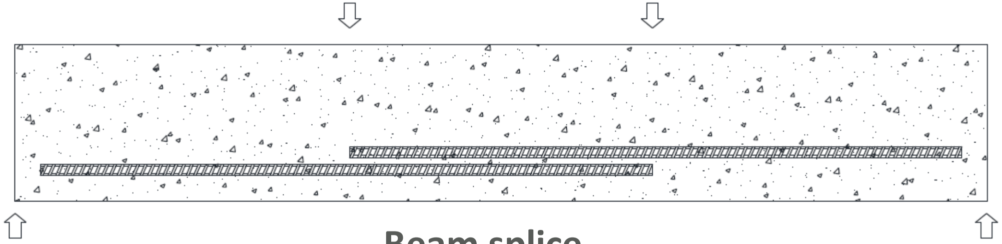
Bond Testing Methods

Approaches:

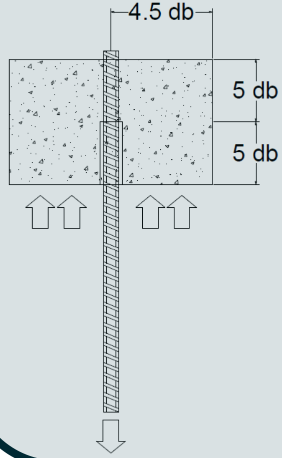
- ❑ Beam Anchorage
- ❑ Beam Splice
- ❑ Beam End
- ❑ Pull-out Test



Beam anchorage

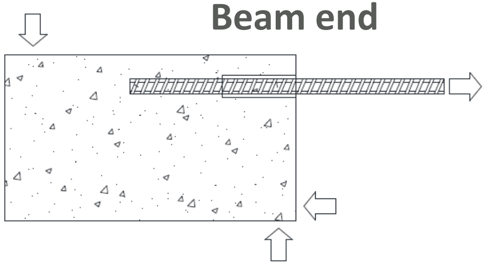


Beam splice



Pull-out test

Beam end



Common bond testing methods [adapted from Alghazali and Myers (2017)]

Background

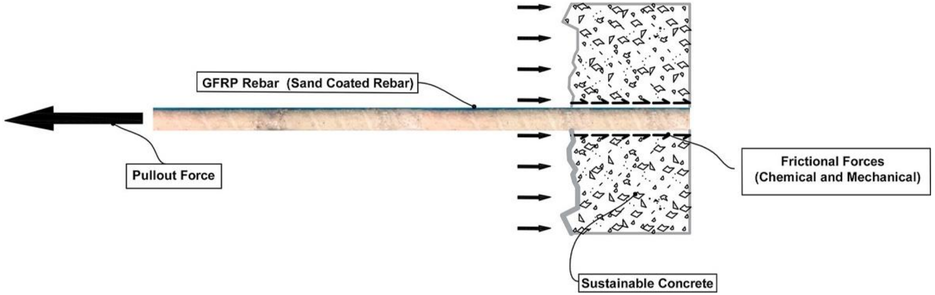
What Influences FRP Bar Bond Performance?

Factors that affect bond performance:

- **Surface treatment** of the FRP bar, which is affected by the bar finish
  - ***deformed or smooth, or any surface treatment*** done on the bar;
- The **mechanical interlock** of the FRP bars against the concrete that may or may not exist;
- The **chemical adhesion** of the bar;
- The **concrete strength (f'_c)**;
- The **type of reinforcing bar**;
- The **elastic modulus (E_f)** of the bar;
- The **placement and concrete cover** of the FRP bar;
- The hydrostatic pressure against the FRP bar due to shrinkage of hardened concrete, and swelling of the FRP rebars due to temperature change and moisture absorption.

Background

How does FRP Bars differ from Mild Steel Bars ?

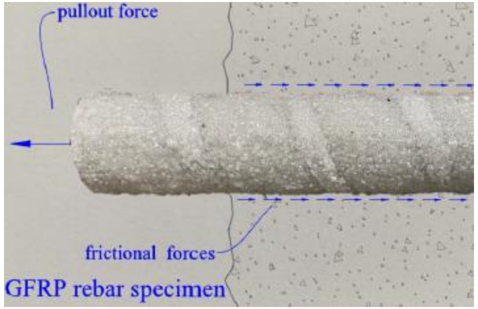


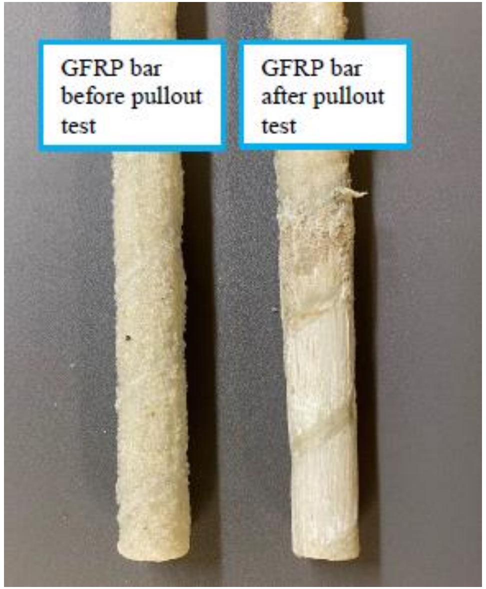
- All **mild steel bars have lugs** and FRP bars typically do not;
- **FRP bars** have more variability in **different surface treatments**;
- Mild steel bars are **homogeneous** (properties generally do not as much as FRP bars, i.e. *fibre alignment and fibre percentage*);
- FRP bars **vary in bar diameter sizes and properties** even within one bar size type (i.e. #4). Therefore, properties vary quite significantly.
- All of this complicates the variability in **FRP bond behaviour** compared to a more standardized reinforcing materials such as **mild steel**.

Background

Direct Tension Failure Modes

- In terms of a direct tension test like the **pull-out test**, there is more than one failure mode that may occur depending on the details of the **reinforcing material**, **specimen geometry** such as clear cover, and **embedded length** of the rebar.
- Common modes of failure include a **splitting failure of the concrete**, a **concrete failure cone pull-out with the bar intact**, or **pull-out of the bar itself from the concrete** as illustrated to the right.
- Difficult to rupture FRP bar as a failure mode possibility.





Research Investigation: Estimating Bond Stress Limits

- In the pull-out test, an **average bond stress** may be considered.

$$\tau = \frac{P}{\pi d_b l_b}$$

where P is the tensile load, d_b is the rebar diameter, and l_b is the embedment length.

- The **maximum developable bar stress** based on **ACI 440.1R-15 Eq. 10.1c** was considered.

$$f_{fe} = \frac{\sqrt{f'_c}}{\alpha}\left(13.6\frac{l_e}{d_b} + \frac{C}{d_b}\frac{l_e}{d_b} + 340\right) \leq f_{fu}$$

When applying Eq. 10.1c for design purposes, ACI 440.1R-15 states ***it should be assumed that the maximum achievable bar stress varies linearly from 0 to the value produced*** *by this Eq. (ACI 440.1R-15 Eq. 10.1c)* ***along the first 20d_b of the bar embedment***.

Research Investigation: Case Study

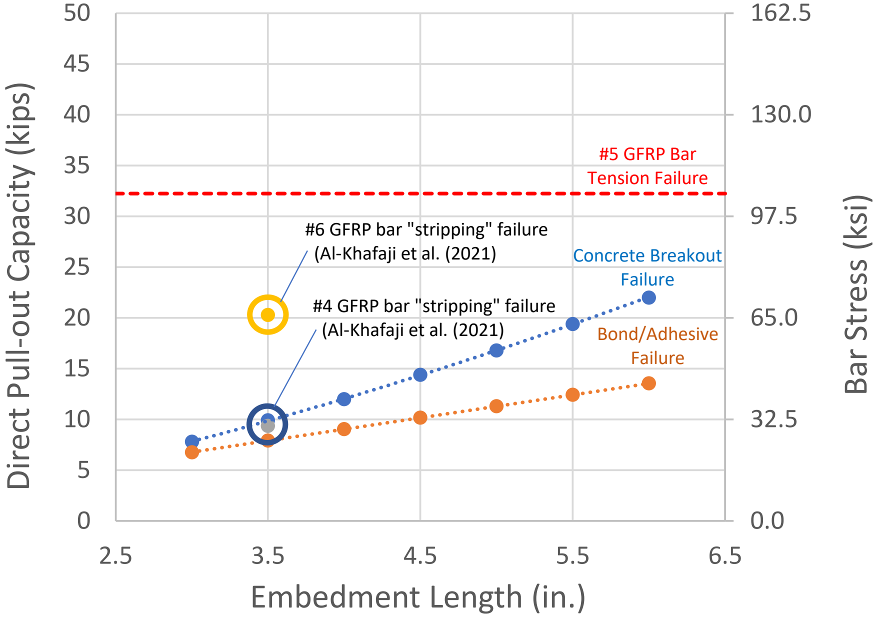
Case Study Analysis

A **case study** was undertaken to explore the **possible failure modes** in a GFRP pull-out analysis for short embedment lengths with adequate cover.

Details of the Case Study Considered:

1. **5000 psi** compressive strength concrete,
2. **#5 GFRP** commercially available bar with tensile strength of **105 ksi**,
3. Modulus of elasticity of **7320 ksi**,
4. and an epoxy shear capacity to concrete of **1150 psi**.

Pull-out Analysis of #5 GFRP Bar in RC



Research Investigation: Literature Review Summary

Data Source	Bar Type (B–C–G)	Bar Size[1] d_{dia} (mm)	Bonded Length, d_b	Special Concrete	Temperature Durability	Microstructure Investigation
Tighiouart et al. (1998)	G	13, 16, 19, 25	6, 10 16	CC		
Katz et al. (1999)	G	13	5	CC	X	
Baena et al. (2009)	C, G	10, 12, 16 (C) 7, 9, 12, 14, 16, 17, 19, 21 (G)	5	CC		
El Refai et al. (2014)	B, G	8, 10, 12 (B) 5, 7, 10, 15 (G)	5, 7, 10, 15	CC		
Lu et al. (2021)	B	12	7	FAC		X
Wang et al. (2021)	B	10, 12, 16	4.2 to 12.5	RAV		
Yoo et al. (2015)	G	13, 16	1, 1.5, 2, 3, 4	UHPFRC		
Hassan et al. (2016)	B	12	5	CC	X	X
Hussain et al. (2022)	B	13, 16, 19	5. 10, 15	HSC	X	X
Al-Khafaji et al. (2021)	G	13, 19	5	HVFAC		
Al-Khafaji et al. (2022a)	G	13, 19	5	EC		X
Al-Khafaji et al. (2022b)	G	13, 19	5	EC		
Subhani et al. (2023)	B, G, C	6	5, 8, 10	CC		

Abbreviations in Table: B – BFRP, C – CFRP, G-GFRP, CC-Conventional Concrete, EC-eco concrete, HSC-high strength concrete, HVFAC-high volume fly ash concrete, FAC-fly ash concrete, RAC-recycled aggregate concrete, UHPFRC-ultra high performance fiber reinforced concrete, X-yes.

Notes: [1]Nominal US FRP bar sizes have been rounded to the closest mm, so #3 (10mm), #4 (13mm), #5 (16mm), #6 (19 mm).

Research Investigation: How to Approach Analysis

- Since the **FRP bar properties** including bar diameter, cross sectional area, tensile capacity, modulus of elasticity, etc. **all vary by manufacturer** as well as the **concrete strength/properties used in the database**, an approach was undertaken to view the pull-out results from the database through the perspective of **upper and lower bandwidths**.
- The **maximum developable bar stress** based on **ACI 440.1R-15 Eq. 10.1c** was considered.

Bond of GFRP Database Analysis

How does published data collected fit to ACI 440.1R-15 Eq. 10.1c ?

Research Investigation: Upper and Lower Limits

GFRP Distribution of Data Collected

These upper and lower values were selected from the experimental research data collected from the publications and align with the variation of the study properties.

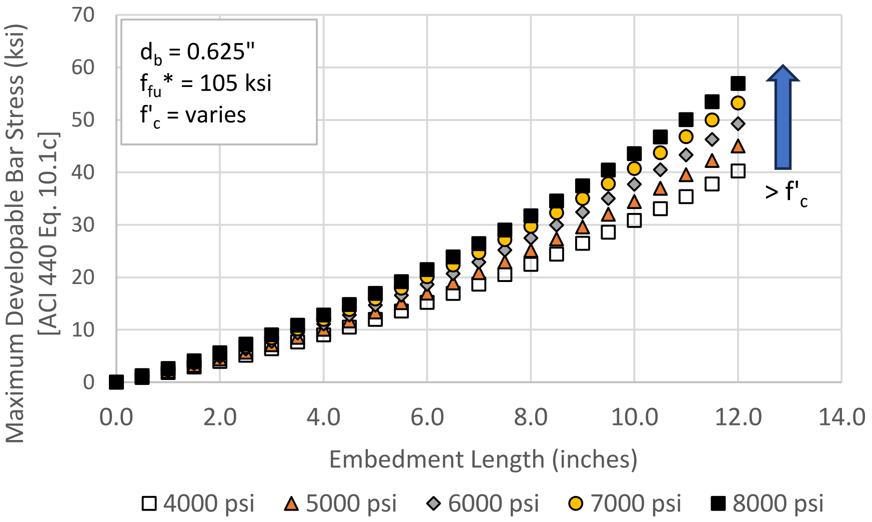
GFRP reinforcing bar size	Bar area (in^2)	Concrete strength (psi)	Bar tension f_{fu}^* (ksi)
#3	0.28-0.40	4000-8000	100-150
#4	0.50-0.54	4000-8000	100-150
#5	0.63-0.68	4000-8000	100-150
#6	0.75-0.84	4000-8000	80-100

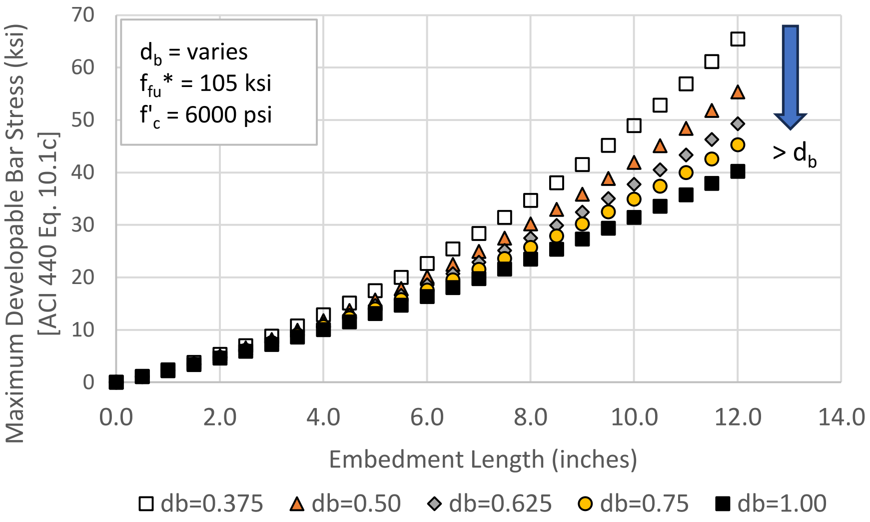
Table note: f_{fu}^* is the guaranteed tensile strength before applying C_e factor per ACI 440.1R-15.

Research Investigation: Upper and Lower Limits

Influence in Parameters on Maximum Developable Stress Eq. 10.1c

Envelopes for **ACI 440.1R-15 Eq. 10.1c** may be developed to determine the maximum developable stress in the bar for given criteria considering the **20d_b** linear adjustment to **zero**.

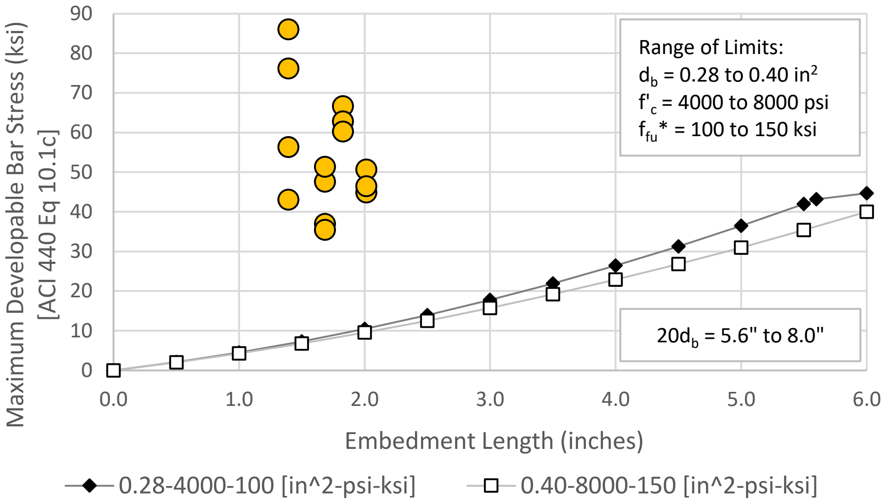




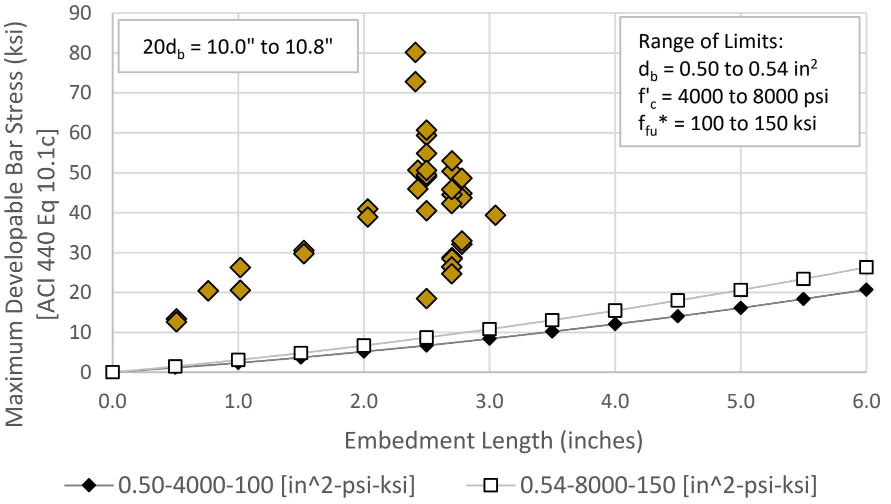
Research Investigation: Upper and Lower Limits

GFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



a) #3 GFRP bar pull-out test results

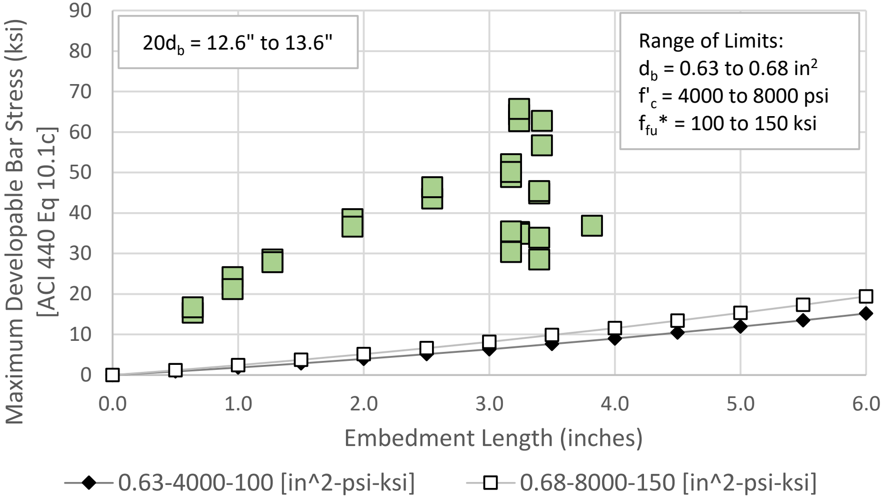


b) #4 GFRP bar pull-out test results

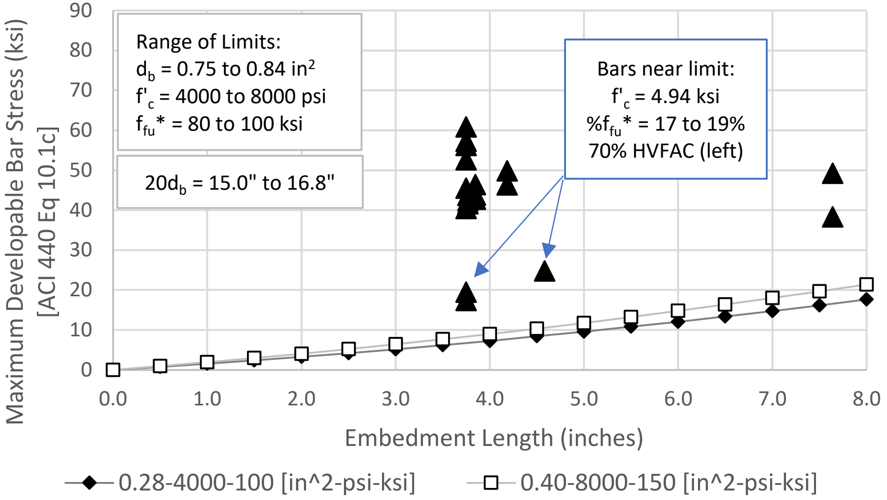
Research Investigation: Upper and Lower Limits

GFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



c) #5 GFRP bar pull-out test results



d) #6 GFRP bar pull-out test results

Research Investigation: General Observations

GFRP Database

- Based upon the data collected, the **#3 GFRP data set Eq. 2 appears quite conservative**.
- The same can be said for **#4 and #5 GFRP dataset**. This is irrespective of the type of concrete or variation in concrete/bar properties.
- In the case of **#6 bars**, some of the test results **yielded results closer to the upper bound limits, but still conservative for the concrete strength**.
- The results show that for **even some specialty concrete like HVFAC**, the developable maximum stress limits appear conservative.

Bond of <u>BFRP</u> Database Analysis

How does published data collected fit to ACI 440.1R-15 Eq. 10.1c ?

Research Investigation: Upper and Lower Limits

BFRP Distribution of Data Collected

These upper and lower values were selected from the experimental research data collected from the publications and align with the variation of the study properties.

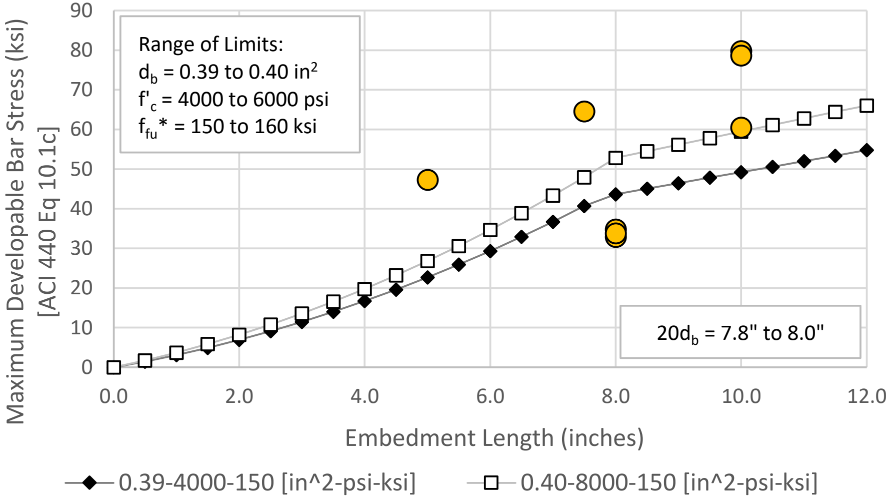
GFRP reinforcing bar size	Bar area (in^2)	Concrete strength (psi)	Bar tension f_{fu}* (ksi)
#3	0.39-0.40	4000-8000	150-160
#4	0.47-0.50	4000-10,000	115-250
#5	0.63	4000-9000	100-150
#6	0.75	4000-9000	113

Table note: f_{fu}* is the guaranteed tensile strength before applying C_e factor per ACI 440.1R-15.

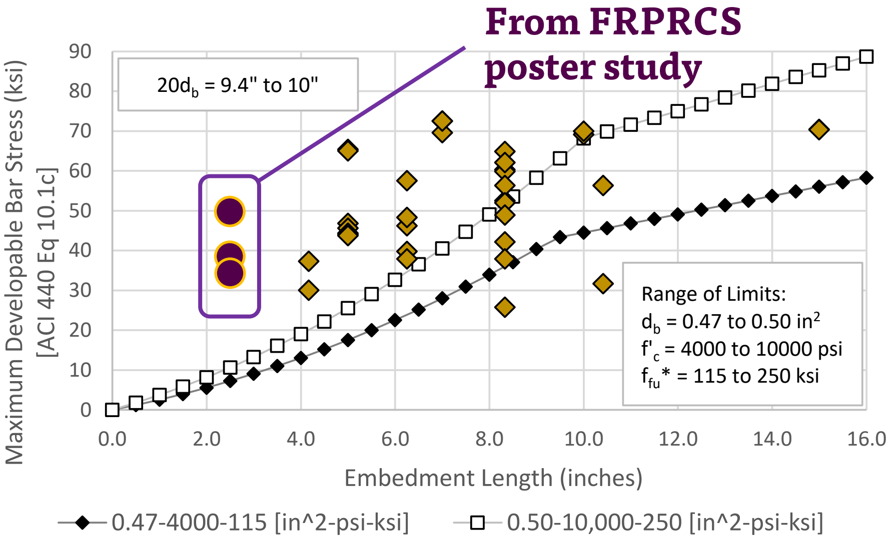
Research Investigation: Upper and Lower Limits

BFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



a) #3 **BFRP** bar pull-out test results

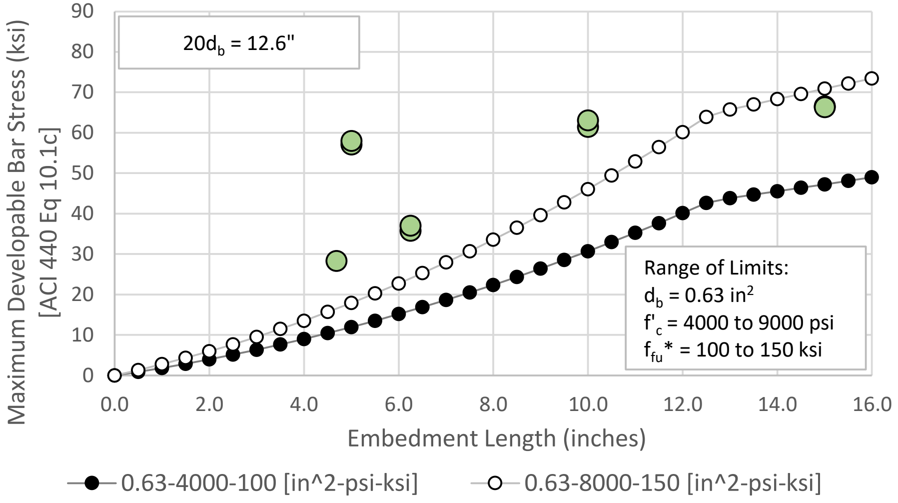


b) #4 **BFRP** bar pull-out test results

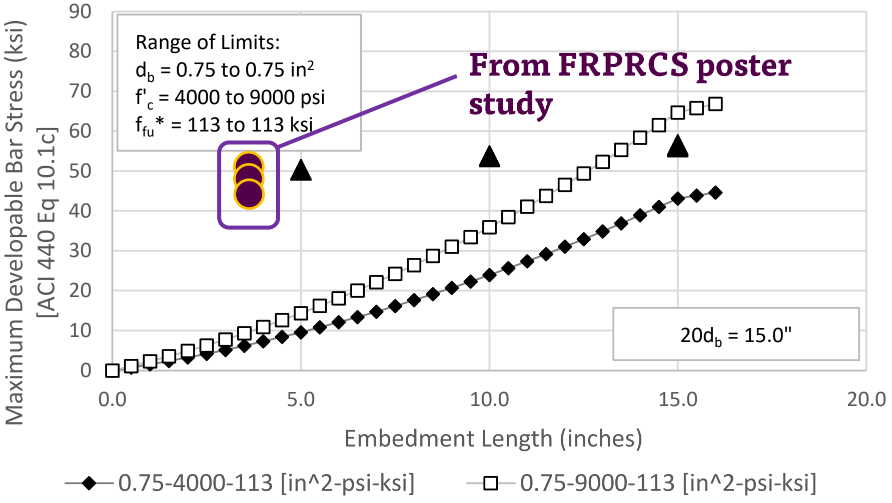
Research Investigation: Upper and Lower Limits

BFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



c) #5 **BFRP** bar pull-out test results



d) #6 **BFRP** bar pull-out test results

Research Investigation: General Observations

BFRP Database

- Based upon the data collected, the **#3 BFRP data set Eq. 2 appears quite scattered with some results unconservative**.
- The same can be said for **#4 BFRP dataset**. This is irrespective of the type of concrete or variation in concrete/bar properties.
- In the case of **#5 and #6 bars**, current data collected in this survey was far too limited to draw conclusions, but **our limited Missouri S&T study appears conservative in both #4 and #6 bars**.
- **Visit FRPRCS 16 Reception Poster Session for more on BFRP Bond Study.**

Bond of CFRP Database Analysis

How does published data collected fit to ACI 440.1R-15 Eq. 10.1c ?

Research Investigation: Upper and Lower Limits

CFRP Distribution of Data Collected

These upper and lower values were selected from the experimental research data collected from the publications and align with the variation of the study properties.

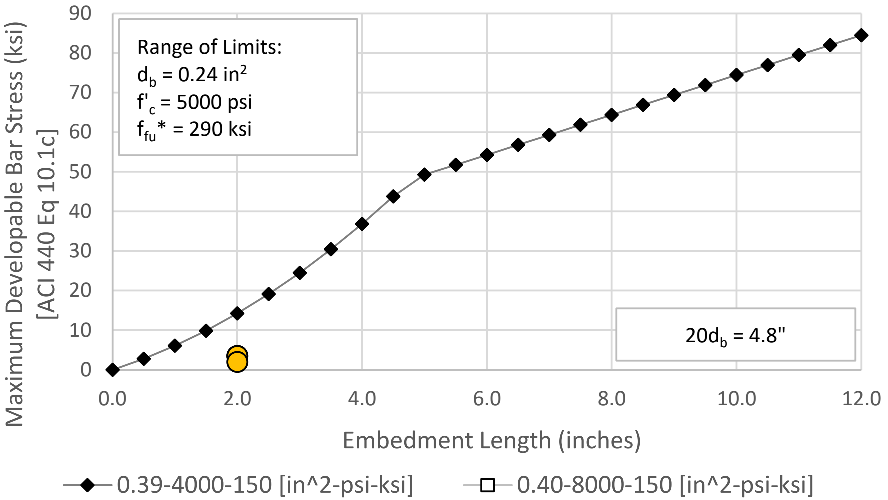
GFRP reinforcing bar size	Bar area (in^2)	Concrete strength (psi)	Bar tension f_{fu}^* (ksi)
#2	0.24	5000	290
#3	0.36-0.42	4000-8000	230-300
#4	0.49-0.53	4000-8000	275-300

Table note: f_{fu}^* is the guaranteed tensile strength before applying C_e factor per ACI 440.1R-15.

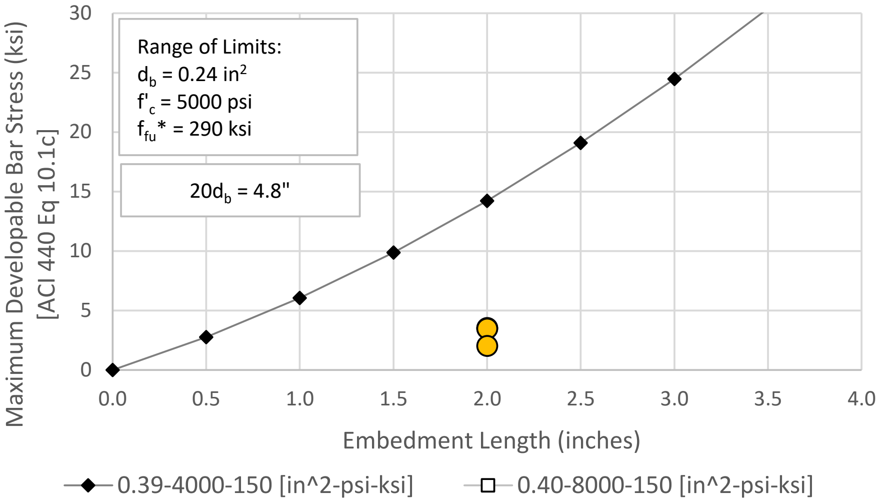
Research Investigation: Upper and Lower Limits

CFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



a) #2 CFRP bar pull-out test results

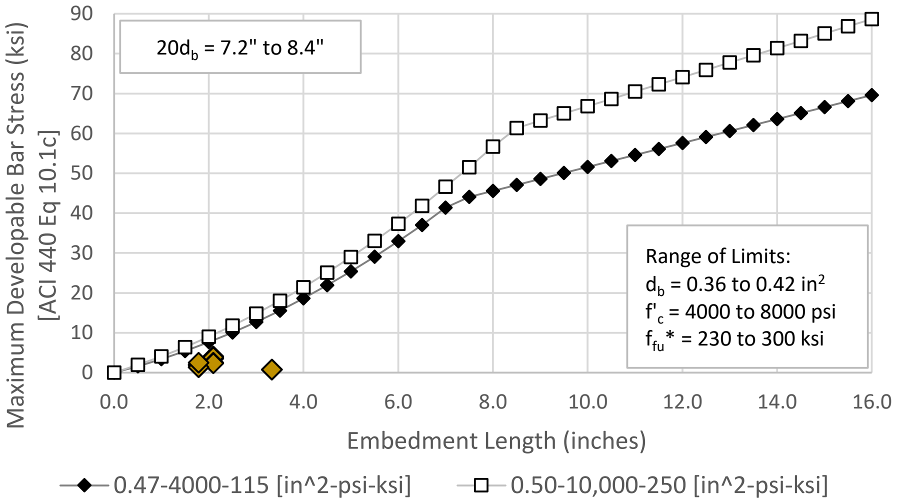


b) #2 CFRP bar pull-out test results (blow-up)

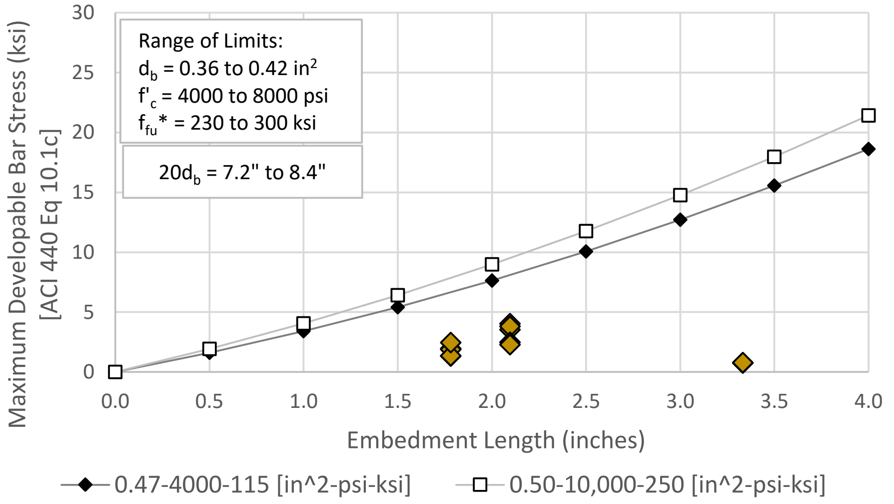
Research Investigation: Upper and Lower Limits

CFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



c) #3 **CFRP** bar pull-out test results

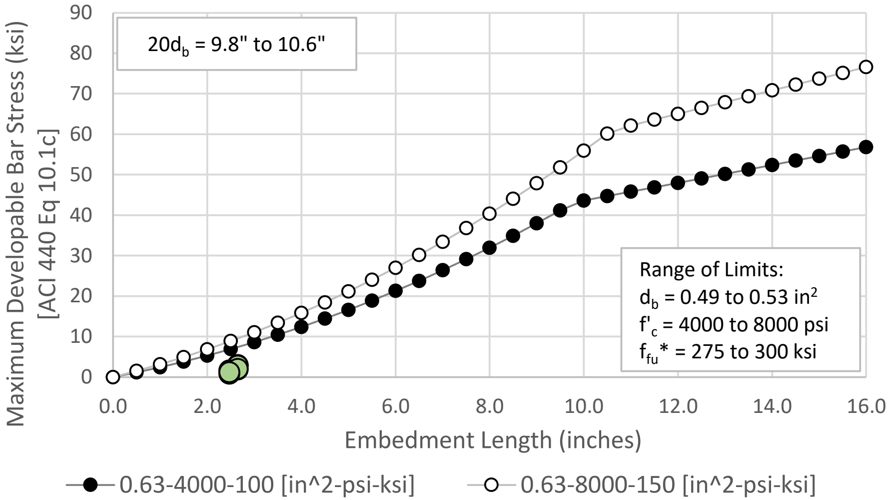


b) #3 **CFRP** bar pull-out test results (blow-up)

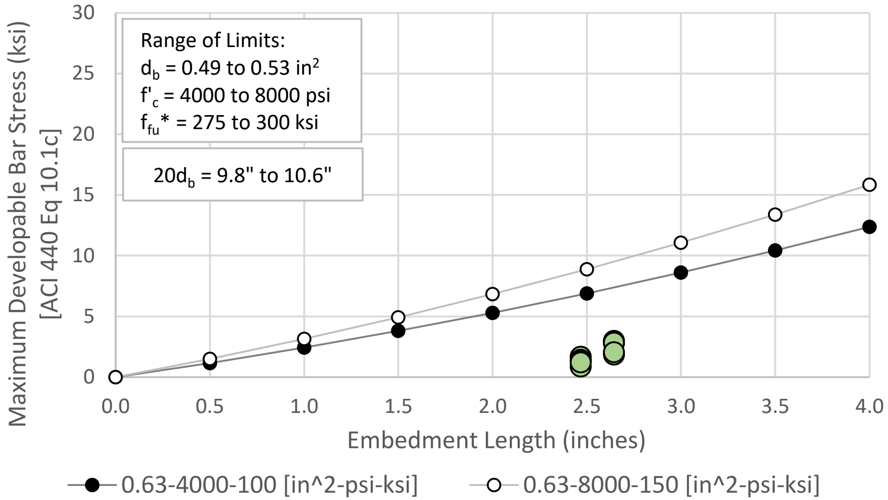
Research Investigation: Upper and Lower Limits

CFRP Database fit to ACI 440.1R-15 Eq. 10.1c

It should be noted that the 0.7 C_e factor has been applied to Eq. 2 (Eq.10.1c) reducing f_{fe}* to f_{fe} as prescribed in ACI 440.1R.



e) #4 CFRP bar pull-out test results



f) #4 CFRP bar pull-out test results (blow-up)

Research Investigation: General Observations

CFRP Database

- Very limited data on **CFRP bars** so **conclusions are difficult to conclude**.
- Based upon the *very limited data collected*, the **#2 CFRP data set Eq. 2 appears unconservative**.
- The same can be said for **#3 and #4 CFRP dataset**. This is irrespective of the type of concrete or variation in concrete/bar properties.
- While limited, data collected raises concerns on the applicability of ACI 440.1r-15 Eq. 10.1.c for use of short CFRP bars.

Concluding Remarks and Take Aways

GFRP Database Pull-out Analysis Results

- Within the range of properties and variables collected within the database, **the variation in the upper and lower limits from ACI 440.1R-15 Eq. 10.1c** are **rather modest for the smaller bar diameters**.
- A large portion of the data within the dataset **developed much higher peak bar stresse**s than limited to by current **ACI 440.1R guidelines**. While research studies show degradation in bond performance, it may be noted that the 0.7 C_e factor was considered in this analysis.

Concluding Remarks and Take Aways

GFRP Database Pull-out Analysis Results

- Current ACI 440.1R **maximum developable bar stress limits appear conservative** for the database collected within this study.
- More investigation is warranted to **examine if any adjustments or calibration factors are warranted** for different grades or type of concrete that utilize GFRP bars to ***make more economic use*** of the FRP materials.

Concluding Remarks and Take Aways

BFRP Database Pull-out Analysis Results

- For the **BFRP data set**, the majority of the data within the data set developed **peak bar stresses at or above the current ACI 440.1R-15 guidelines**. However, **approximately 15% of the data set appeared to be unconservative**. For the data set collected, it appears that the bond behavior of BFRP bars currently produced and evaluated in pull out testing to yield **somewhat reduced bond behavior**. It may be noted that a 0.7 C_e factor was considered in this analysis.
- Current ACI 440.1R-15 maximum developable bar stress limits **appear unconservative for a statistically significant number of test results** in the BFRP database collected within this study.

Concluding Remarks and Take Aways

CFRP Database Pull-out Analysis Results

- For the **CFRP data set**, it may be noted that firstly, the **data collected was quite limited** thus leading to ***caution drawing any hard conclusions***. As mentioned, of the FRP bars data collected, **CFRP bars are least likely to be used in a short embedment situation**. One key observation is that the current ACI 440.1R-15 Eq. 10.1c guidelines which may be applied to any of the three FRP bars **appear to not capture the short bond behavior of this bar grouping**. It may be noted that a 0.9 C_e factor was considered in this analysis.
- Current ACI 440.1R-15 maximum developable bar stress limits appear **unconservative** for the **limited CFRP database collected** within this study.

Future and Ongoing Work

- Continue to add to the pull-out database on **GFRP, BFRP and CFRP bars** and fit available the data.
- To determine any gaps in experimental test data.
- To investigate and determine **bond performance** for FRP bars that are epoxy doweled and embedded into concrete.
- To further evaluate the **bond performance** for FRP bars coated with MKPC paste **in reduced embedment length scenarios**.
- Expand work to investigate and determine **shear friction performance** for FRP bars that are embedded and epoxied embedded into concrete.

Future and Ongoing Work

- More work recommended to expand the current database **by surface treatment** to better understand if **calibration factors** for each grouping **are warranted**.
- More work **needs to be undertaken** to fully understand the **bond behavior of adhesively anchored embedded GFRP bars** and their **long-term durability behavior** since this study indicated **it may be a prominent failure mode in pull-out** when used in field applications to bond GFRP bars. While some studies have been undertaken, more data on a larger set of variables is still needed. Guidelines in ACI 440 are recommended to aid practitioners using FRP bars in adhesively bonded dowel applications.

Acknowledgements

- Thanks to **Sadeq Annooz** at Missouri S&T for assisting to collect a number of the papers for this literature review that made up the database for study.
- The author would like to acknowledge the office of **Wiss, Janey, Elstner Associates, Inc. (WJE)** in **Austin, Texas** and in particular thank **Carl J. 'Chuck' Larosche**, **Dr. Jeffery S. West**, **Lee B. Lawrence**, **Stephen W. Foster**, **Matt P. Carlton**, and **Brian D. Merrill**. The inspiration to examine this topic of *short embedment length* and develop this paper was a result of the author's opportunity to be hosted by WJE on sabbatical and discuss field challenges. The author thanks this highly talented group of engineers and scientists that bring theory and practice to harmony and the opportunity to collaborate while on sabbatical.

MCTI
MISSOURI CENTER FOR
TRANSPORTATION
INNOVATION
PROPELLING PEOPLE · CONNECTING COMMUNITIES · ENERGIZING ECONOMIES

Missouri University of Science and Technology

MISSOURI S&T

Thank You!

John J. Myers

Email contact: JMyers@mst.edu

March 23, 2024