American Concrete Institute®
Advancing concrete knowledge

Strengthening of Masonry Structures

ACI Spring 2011 Convention
April 3 - 7, Tampa, FL

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Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

DATE	LOCATION	DATE	LOCATION
September 13	Chicago, IL	November 3	Charlotte, NC
September 27	Philadelphia, PA	November 8	Boston, MA
September 29	Houston, TX	November 10	Detroit, MI
October 4	Seattle, WA	November 15	Des Moines, IA
October 6	Los Angeles, CA	November 17	Portland, OR
October 11	New York, NY	November 29	Denver, CO
October 13	Minneapolis, MN	December 1	Phoenix, AZ
October 20	Cincinnati, OH	December 6	Atlanta, GA
October 25	New Brunswick, NJ	December 8	Washington, DC
October 27	St. Louis, MO	December 13	Dallas, TX
November 1	Orlando, FL	December 15	San Francisco, CA

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ACI Web Sessions

This ACI Web Session includes two speakers presenting at the ACI spring convention held in Tampa, FL April 3 – 7, 2011.

Additional presentations will be made available in future ACI Web Sessions.

Please enjoy the presentations.

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Strengthening of Masonry Structures

ACI Spring 2011 Convention
April 3 - 7, Tampa, FL

Lawrence C. Bank, ACI member and professor in the Department of Civil and Environmental Engineering at the University of Wisconsin in Madison. Dr. Bank's primary research is in the area of the mechanics and design of composite material structures with an emphasis on applications to civil engineering. He is the author of the textbook Composites for Construction: Structural Design with FRP Materials. He is a member of ACI Committee 440 – Fiber-Reinforced Polymer Reinforcement.

FRP Reinforcement for Reinforced Concrete Structures (FRPRCS-10) | ACI Committee 440

Experimental studies of mechanically fastened FRP systems: state-of-the-art

V.L. Brown, L.C. Bank*, D. Arora, D.T. Borowicz, A. Godat, A.J. Lamanna, J. Lee, F. Matta, A. Napoli, K.-H. Tan

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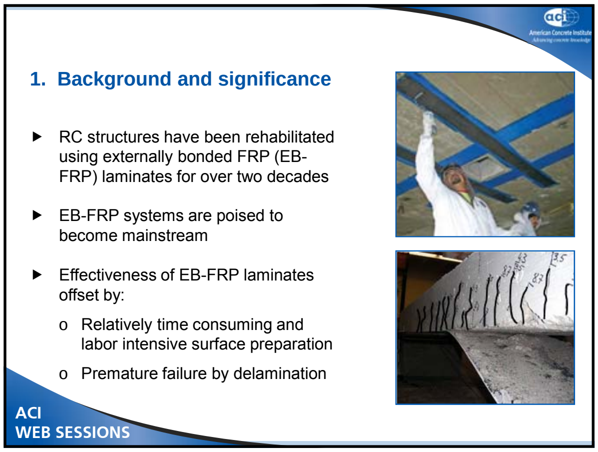
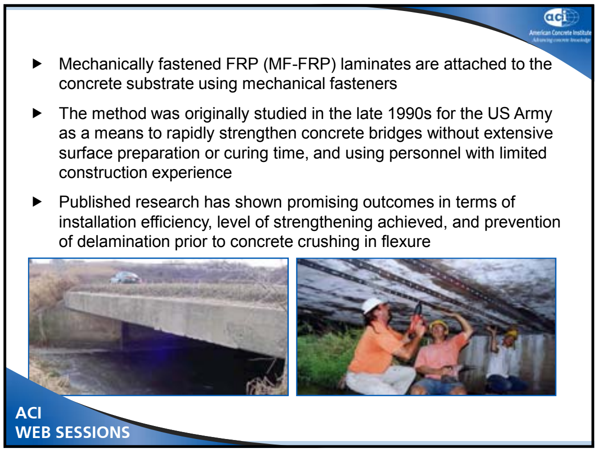
Outline

1. Background and significance
2. Properties of FRP strips
3. Beams and one-way slabs
4. Two-way slabs
5. Field demonstrations
6. Conclusions



1. Background and significance

- RC structures have been rehabilitated using externally bonded FRP (EB-FRP) laminates for over two decades
- EB-FRP systems are poised to become mainstream
- Effectiveness of EB-FRP laminates offset by:
    - o Relatively time consuming and labor intensive surface preparation
    - o Premature failure by delamination



- Mechanically fastened FRP (MF-FRP) laminates are attached to the concrete substrate using mechanical fasteners
- The method was originally studied in the late 1990s for the US Army as a means to rapidly strengthen concrete bridges without extensive surface preparation or curing time, and using personnel with limited construction experience
- Published research has shown promising outcomes in terms of installation efficiency, level of strengthening achieved, and prevention of delamination prior to concrete crushing in flexure

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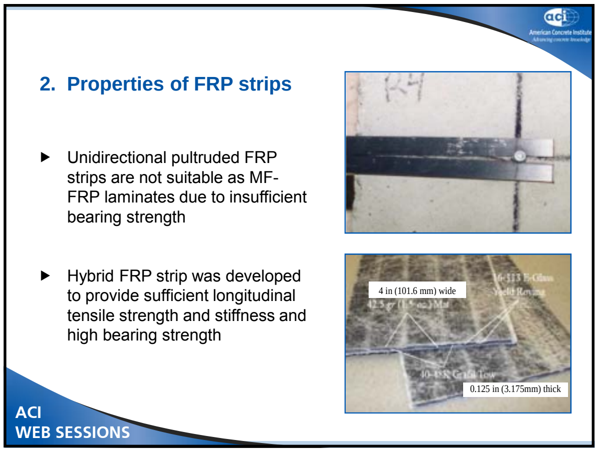

2. Properties of FRP strips

- Unidirectional pultruded FRP strips are not suitable as MF-FRP laminates due to insufficient bearing strength
- Hybrid FRP strip was developed to provide sufficient longitudinal tensile strength and stiffness and high bearing strength

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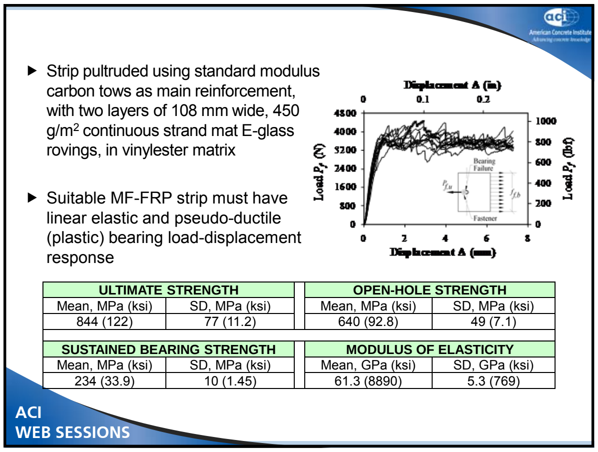
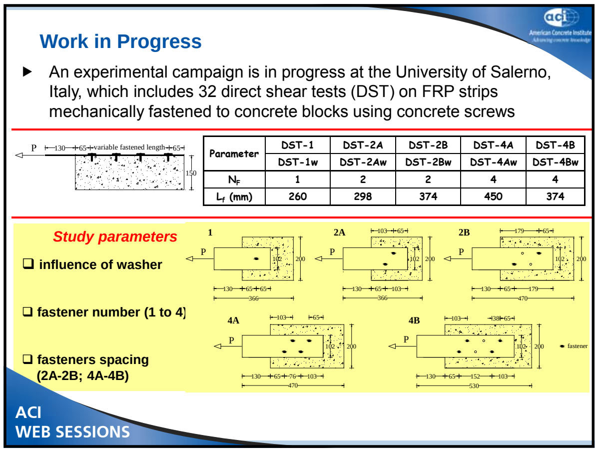


- Strip pultruded using standard modulus carbon tows as main reinforcement, with two layers of 108 mm wide, 450 g/m^2 continuous strand mat E-glass rovings, in vinylester matrix
- Suitable MF-FRP strip must have linear elastic and pseudo-ductile (plastic) bearing load-displacement response

ULTIMATE STRENGTH		OPEN-HOLE STRENGTH	
Mean, MPa (ksi)	SD, MPa (ksi)	Mean, MPa (ksi)	SD, MPa (ksi)
844 (122)	77 (11.2)	640 (92.8)	49 (7.1)

SUSTAINED BEARING STRENGTH		MODULUS OF ELASTICITY	
Mean, MPa (ksi)	SD, MPa (ksi)	Mean, GPa (ksi)	SD, GPa (ksi)
234 (33.9)	10 (1.45)	61.3 (8890)	5.3 (769)



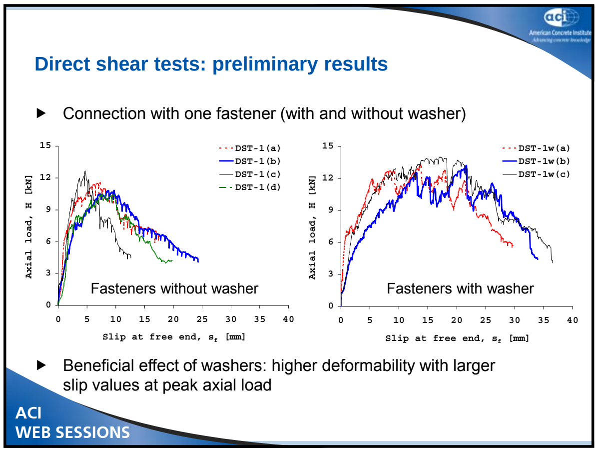
Work in Progress

- An experimental campaign is in progress at the University of Salerno, Italy, which includes 32 direct shear tests (DST) on FRP strips mechanically fastened to concrete blocks using concrete screws

Parameter	DST-1 DST-1w	DST-2A DST-2Aw	DST-2B DST-2Bw	DST-4A DST-4Aw	DST-4B DST-4Bw
N_F	1	2	2	4	4
L_f (mm)	260	298	374	450	374

Study parameters

- ❑ **influence of washer**
- ❑ **fastener number (1 to 4)**
- ❑ **fasteners spacing (2A-2B; 4A-4B)**



Direct shear tests: preliminary results

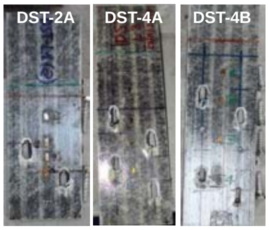
- Connection with one fastener (with and without washer)

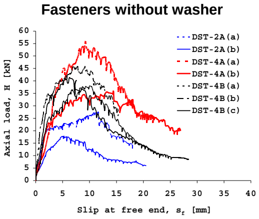
Fasteners without washer

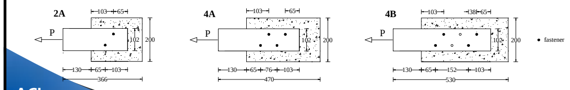
Fasteners with washer

- Beneficial effect of washers: higher deformability with larger slip values at peak axial load

- Connection with multiple fasteners (with and without washers)







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3. Beams and one-way slabs

- Database provides convenient information source for published data on performance of MF-FRP strengthened beams and one-way slabs
- Database is organized according to type of fastening system: power actuated fasteners (PAF), concrete screws or expansion anchor bolts

Beam ID	Beam span mm	Shear span mm	Cross section	f'_c MPa	b mm	h mm	d mm	A_s mm^2
References: Lamanna 2002, Bank et al. 2002a								
All 12 beams in series	3350	1120	Square	32.7	305	305	253	1020
References: Borowicz 2002, Bank et al. 2002b								
UW2	3505	1370	Square	44.7	305	305	254	1020
UW3	3505	1370	Square	44.7	305	305	254	1020
UW4	2130	686	Square	44.7	305	305	254	1020
UW5	2640	940	Square	44.7	305	305	254	1020
UW6	3350	1295	Square	44.7	305	305	254	1020
UW7	3450	1350	Square	44.7	305	305	254	1020
UW8	3505	1370	Square	44.7	305	305	254	1020
UW9	3505	1370	Square	44.7	305	305	254	1020
UW10	3505	1370	Square	44.7	305	305	254	1020
A3-1	8530	3505	T-Beam	29.6	1520	762	683	1935
A3-2	8530	3505	T-Beam	32.8	1520	762	683	1935
A5-1	8530	3505	T-Beam	33.3	1520	762	660	3225
A5-2	8530	3505	T-Beam	29.6	1520	762	660	3225
A8-1	8530	3505	T-Beam	31.6	1520	762	638	5160
A8-2	8530	3505	T-Beam	34.3	1520	762	638	5160
Reference: Arora 2003								
FRP 1	6530	2870	Square	41.1	508	508	470	1160
FRP 2SS	6530	2870	Square	41.5	508	508	470	1160
FRP 3	6530	2870	Square	41.2	508	508	470	1160
Reference: Bank et al. 2004a								
All 5 beams in series	8530	3505	T-Beam	34.5	1520	762	660	3230
Reference: Lee et al. 2009								
All 3 beams in series	1420	610	Rect.	28.8	150	200	160	258

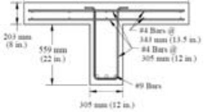
Beam ID	Beam span mm	Shear span mm	Cross section	f'_c MPa	b mm	h mm	d mm	A_s mm^2
Reference: Ekenel et al. 2006								
S-4F	1830	762	Rect.	27.6	254	165	122	213
Reference: Galati et al. 2007								
MFP2	2200	800	Rect.	31.5	200	250	221	258
Reference: Marks et al. 2007								
All 8 beams in series	2290	1070	Rect.	42.7	203	152	114	258
Reference: Martin & Lamanna 2008								
All 6 beams in series	3350	1220	Square	48	305	305	242	1020
References: Napoli 2008, Napoli et al. 2010								
MF-1-L	3050	1220	Slab	28.5	305	152	127	387
MF-1-S	3050	1220	Slab	28.5	305	152	127	387
MF-2-L	3050	1220	Slab	25.5	305	152	127	387
MF-2-S	3050	1220	Slab	25.5	305	152	127	387
Reference: Fung et al. 2010								
2-#4-R4-88	2290	1070	Rect.	36.2	203	152	114	258
3-#4-S4-88	2290	1070	Rect.	36.2	203	152	114	258
4-#4-S3-88	2290	1070	Rect.	36.2	203	152	114	258
5-#4-S4-60	2290	1070	Rect.	36.2	203	152	114	258
6-#4-S3-46	2290	1070	Rect.	36.2	203	152	114	258
7-#4-S3-60	2290	1070	Rect.	36.2	203	152	114	258
8-#3-S4-88	2290	1070	Rect.	36.2	203	152	114	142
9-#4-S4-46	2290	1070	Rect.	36.2	203	152	114	258
10-#3-L4-88	2290	1070	Rect.	36.2	203	152	114	142

- Early study by Lamanna (2002) on 35 scaled (152 x 152 x 1220 mm) RC beams. Feasibility was evaluated using different fasteners and layouts, and different FRP laminates
- 12 larger scale beams (305 x 305 x 3660 mm) were then tested (Lamanna 2002, Bank et al. 2002) to study influence of fastener type and spacing, pre-drilling of FRP strips, and type and number of FRP strips
- Additional 9 beams (305 x 305 x 3660 mm) were tested (Borowicz 2002, Bank et al. 2002) to study anchorage length, shear spans, fatigue loads, and type and number of FRP strips

Lamanna (2002)

Lamanna (2002), Bank et al. (2002)

- Six full-scale T-beams were tested (Borowicz 2002, Bank et al. 2002), followed by additional 5 specimens (Bank et al. 2004), to investigate:
  - o Concrete expansion anchors at the FRP strip ends to prevent delamination
  - o Use of multiple FRP strips, also investigated by Arora (2003)
- Fastener types and layouts were studied by Lee et al. (2009) drawing evidence from tests on three beam specimens (150 x 200 x 1520 mm)



Borowicz (2002)

General conclusions

- Ductile failure mode by concrete crushing after steel yield, with FRP strips firmly attached
- With appropriate fastener layout and FRP strip properties, the strength increase is equal to that of EB-FRP strengthened beams, with a slightly lesser stiffness but with a much greater ductility
- Use of multiple FRP strips in unbonded layers does not yield significant increases in capacity over that of beams strengthened with a single strip, attributed to premature end-delamination and fasteners' inability to transfer load into the outer strips
- Strains in the FRP are smaller than predicted by the fully bonded assumption, leading to the conclusion that slip accommodated by nail rotation decreases strengthening effectiveness

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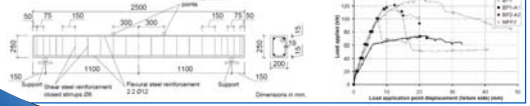
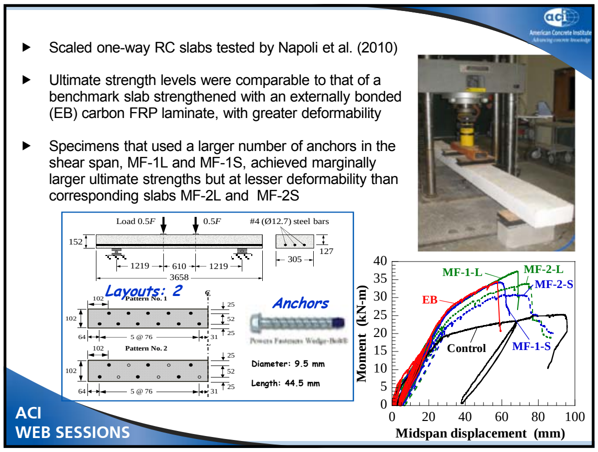
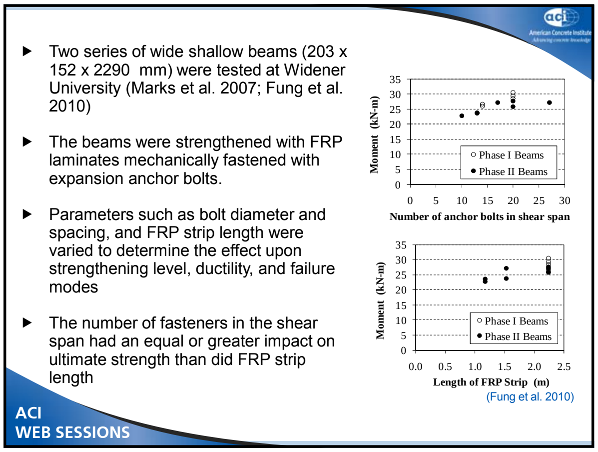
- An MF-FRP strengthened beam (MFP2) was tested and compared to (Galati et al. 2007):
  - o 2 beams strengthened by epoxy bonded unidirectional CFRP pre-cured laminates (BP1 epoxy only, and BP1-A1 with fiber anchor spikes)
  - o a beam using the same hybrid pre-cured laminate bonded with epoxy and with steel anchors at the strip ends (BP2-A2)
- 6 concrete beams (305 x 305 x 3657 mm) were strengthened (Martin & Lamanna 2004) using relatively large diameter (12.7mm) concrete screws to investigate:
  - o the effect of fastener number, spacing, and pattern

Tests by Galati et al. (2007)





- Scaled one-way RC slabs tested by Napoli et al. (2010)
- Ultimate strength levels were comparable to that of a benchmark slab strengthened with an externally bonded (EB) carbon FRP laminate, with greater deformability
- Specimens that used a larger number of anchors in the shear span, MF-1L and MF-1S, achieved marginally larger ultimate strengths but at lesser deformability than corresponding slabs MF-2L and MF-2S



- Two series of wide shallow beams (203 x 152 x 2290 mm) were tested at Widener University (Marks et al. 2007; Fung et al. 2010)
- The beams were strengthened with FRP laminates mechanically fastened with expansion anchor bolts.
- Parameters such as bolt diameter and spacing, and FRP strip length were varied to determine the effect upon strengthening level, ductility, and failure modes
- The number of fasteners in the shear span had an equal or greater impact on ultimate strength than did FRP strip length

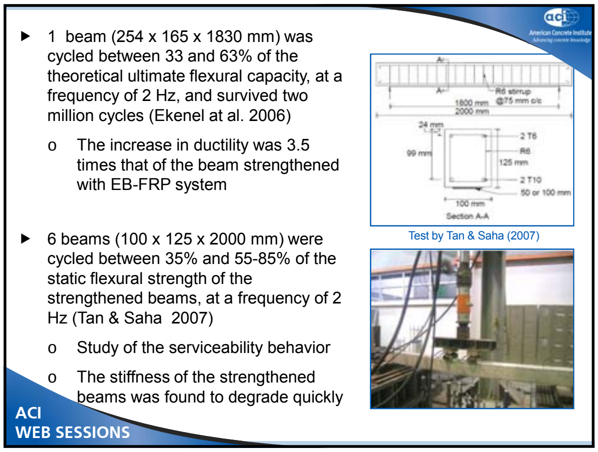
(Fung et al. 2010)

General conclusions

- As with PAFs, the efficiency of concrete screws is affected by hard aggregates
- The gradual bearing failure of screws through the FRP strip, coupled with yielding of steel reinforcement, produces significant deflections
- The ultimate strength levels are comparable to those of EB-FRP strengthened slabs, with greater deformability
- Increasing the numbers of anchors, specimens achieve marginally larger ultimate strengths but at lesser deformability
- The number of fasteners in the shear span has an equal or greater impact on ultimate strength than does FRP strip length
- FRP strains are less than those calculated assuming fully bonded conditions; strain efficiency tends to increase as the number of anchor bolts increases

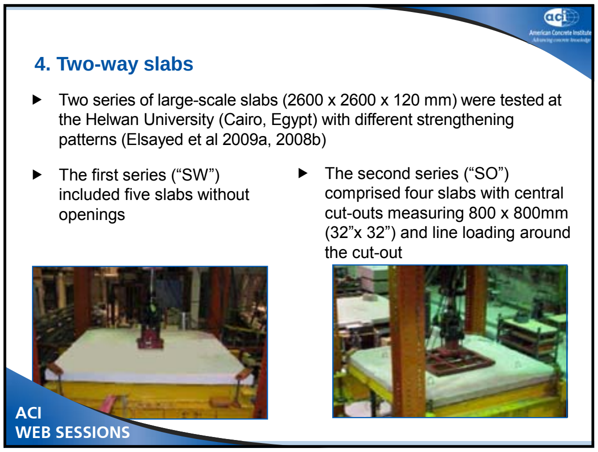
Fatigue Tests

- 2 beams (305 x 305 x 1370 mm) were subjected to cyclic loading between 20 and 80% of unstrengthened beam capacity at a 2 Hz frequency in four-point bending (Borowicz 2002)
  - FRP showed no signs of degradation, and fasteners remained firmly embedded in concrete
- 1 full-size T beam was tested between 44.5 and 133.4 kN at 2 Hz for 2,000,000 cycles without beam failure (Bank et al. 2004a)
  - no FRP or fastener wear was noted
- 6 beams (152 x 254 x 4750 mm) were tested under midpoint flexure (Quattlebaum et al. 2005)
  - # 3 flexural retrofit systems compared: MF-FRP, near-surface mounted (NSM), and adhesively bonded (EB) systems
  - MF-FRP strengthened beams outperformed NSM-FRP and EB-FRP strengthened beams in high-stress range fatigue life
  - For beams subjected to low-stress fatigue, the MF-FRP strengthened beam showed less damage compared to the EB-FRP one



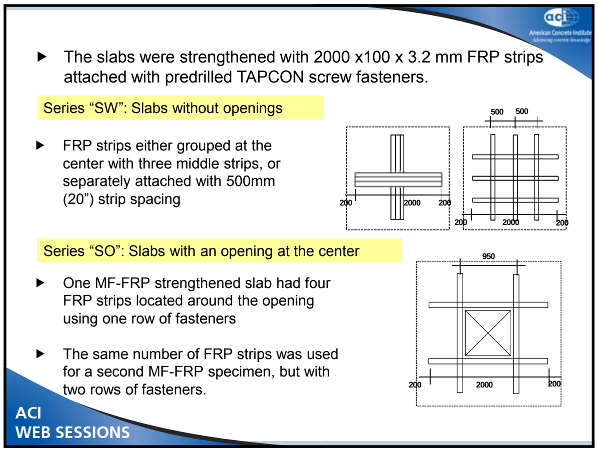
- 1 beam (254 x 165 x 1830 mm) was cycled between 33 and 63% of the theoretical ultimate flexural capacity, at a frequency of 2 Hz, and survived two million cycles (Ekenel at al. 2006)
  - The increase in ductility was 3.5 times that of the beam strengthened with EB-FRP system
- 6 beams (100 x 125 x 2000 mm) were cycled between 35% and 55-85% of the static flexural strength of the strengthened beams, at a frequency of 2 Hz (Tan & Saha 2007)
  - Study of the serviceability behavior
  - The stiffness of the strengthened beams was found to degrade quickly

Test by Tan & Saha (2007)



4. Two-way slabs

- Two series of large-scale slabs (2600 x 2600 x 120 mm) were tested at the Helwan University (Cairo, Egypt) with different strengthening patterns (Elsayed et al 2009a, 2008b)
- The first series (“SW”) included five slabs without openings
- The second series (“SO”) comprised four slabs with central cut-outs measuring 800 x 800mm (32”x 32”) and line loading around the cut-out

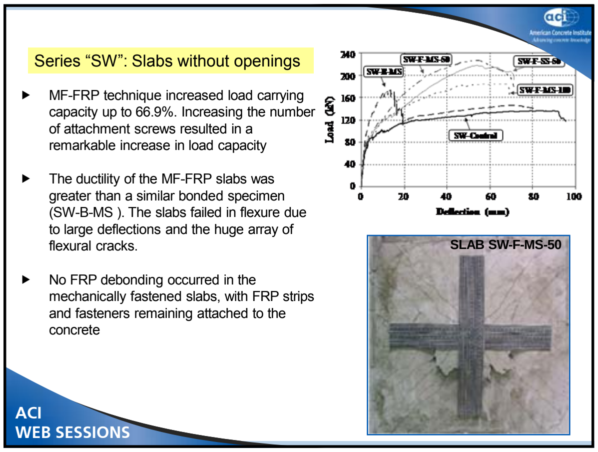

- The slabs were strengthened with 2000 x100 x 3.2 mm FRP strips attached with predrilled TAPCON screw fasteners.

Series “SW”: Slabs without openings

- FRP strips either grouped at the center with three middle strips, or separately attached with 500mm (20”) strip spacing

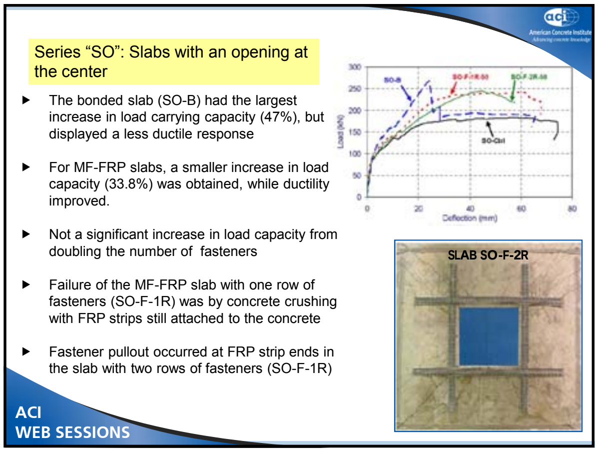
Series “SO”: Slabs with an opening at the center

- One MF-FRP strengthened slab had four FRP strips located around the opening using one row of fasteners
- The same number of FRP strips was used for a second MF-FRP specimen, but with two rows of fasteners.


Series “SW”: Slabs without openings

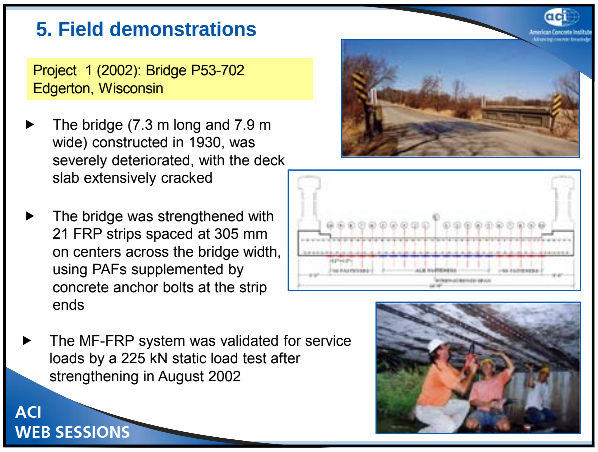
- MF-FRP technique increased load carrying capacity up to 66.9%. Increasing the number of attachment screws resulted in a remarkable increase in load capacity
- The ductility of the MF-FRP slabs was greater than a similar bonded specimen (SW-B-MS). The slabs failed in flexure due to large deflections and the huge array of flexural cracks.
- No FRP debonding occurred in the mechanically fastened slabs, with FRP strips and fasteners remaining attached to the concrete

SLAB SW-F-MS-50


Series “SO”: Slabs with an opening at the center

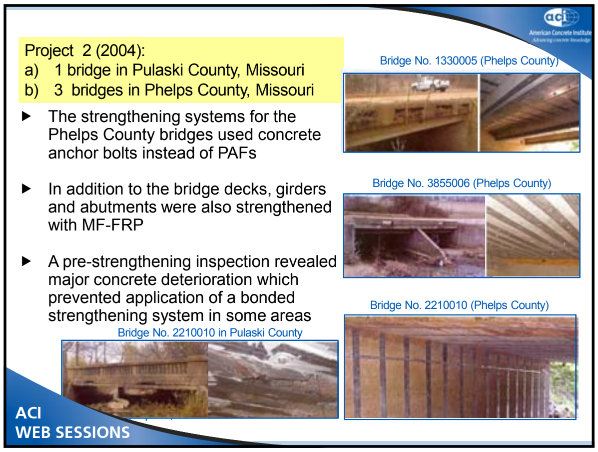
- The bonded slab (SO-B) had the largest increase in load carrying capacity (47%), but displayed a less ductile response
- For MF-FRP slabs, a smaller increase in load capacity (33.8%) was obtained, while ductility improved.
- Not a significant increase in load capacity from doubling the number of fasteners
- Failure of the MF-FRP slab with one row of fasteners (SO-F-1R) was by concrete crushing with FRP strips still attached to the concrete
- Fastener pullout occurred at FRP strip ends in the slab with two rows of fasteners (SO-F-1R)

SLAB SO-F-2R


5. Field demonstrations

Project 1 (2002): Bridge P53-702 Edgerton, Wisconsin

- The bridge (7.3 m long and 7.9 m wide) constructed in 1930, was severely deteriorated, with the deck slab extensively cracked
- The bridge was strengthened with 21 FRP strips spaced at 305 mm on centers across the bridge width, using PAFs supplemented by concrete anchor bolts at the strip ends
- The MF-FRP system was validated for service loads by a 225 kN static load test after strengthening in August 2002


Project 2 (2004):
a) 1 bridge in Pulaski County, Missouri
b) 3 bridges in Phelps County, Missouri

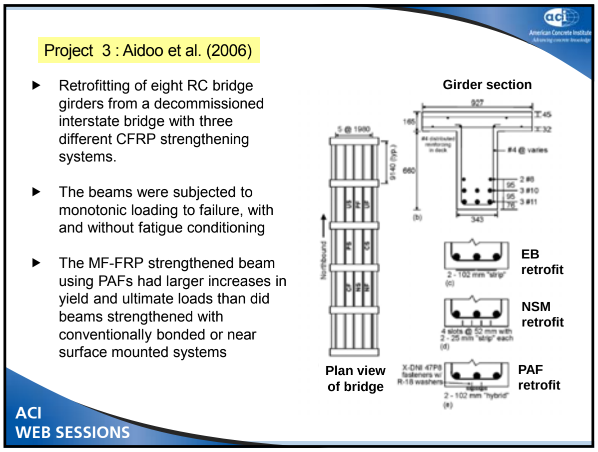
- The strengthening systems for the Phelps County bridges used concrete anchor bolts instead of PAFs
- In addition to the bridge decks, girders and abutments were also strengthened with MF-FRP
- A pre-strengthening inspection revealed major concrete deterioration which prevented application of a bonded strengthening system in some areas

Bridge No. 1330005 (Phelps County)

Bridge No. 3855006 (Phelps County)

Bridge No. 2210010 (Phelps County)

Bridge No. 2210010 in Pulaski County


Project 3 : Aidoo et al. (2006)

- Retrofitting of eight RC bridge girders from a decommissioned interstate bridge with three different CFRP strengthening systems.
- The beams were subjected to monotonic loading to failure, with and without fatigue conditioning
- The MF-FRP strengthened beam using PAFs had larger increases in yield and ultimate loads than did beams strengthened with conventionally bonded or near surface mounted systems

Girder section

Plan view of bridge

EB retrofit

NSM retrofit

PAF retrofit

6. Conclusions

- An overview of the experimental research on the MF-FRP method has been presented
- A database of collected test results has been assembled to provide a convenient source of information on published test data on the performance of MF-FRP strengthened beams and one-way slabs
- It can be concluded that the MF-FRP method is a viable technique for strengthening concrete members, particularly where speed of installation and immediacy of use are imperative, or where strengthening is intended as a temporary measure
- The method is particularly attractive because little surface preparation is required and a pseudo-ductile failure mode is obtained

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- Andrea Rizzo, *University of Lecce*

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ACI Design Guide for Flexural and Shear Strengthening of URM Walls with FRP Systems

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…ced Polymer Reinforcement for Concrete Structures
10th International Symposium

INTRODUCTION

- Unreinforced masonry (URM) structures are prone to extensive damage due to loads from wind, earthquake or man-made events
  - FRP composites can offer solutions for masonry strengthening
- Need for masonry strengthening requires development of guides for design, handling and installation of the externally bonded FRP systems
- In 2010, the ACI Committee 440 published "Guide for the Design and Construction of Externally Bonded FRP Systems for Unreinforced Masonry Structures" (ACI 440.7R-10)
  - Flexural Strengthening
  - Shear Strengthening

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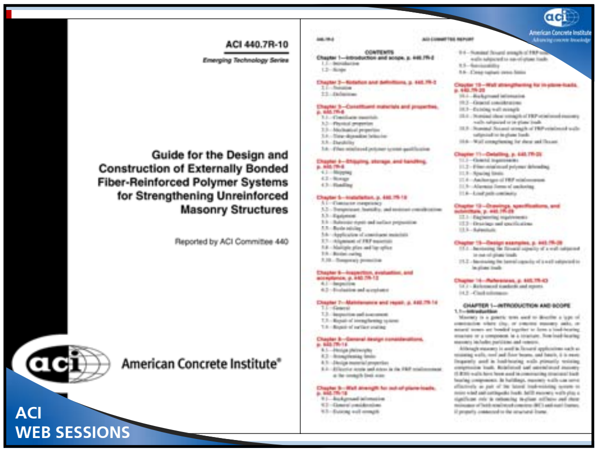

ACI 440.7R-10
Emerging Technology Series

Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures

Reported by ACI Committee 440

American Concrete Institute®

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE

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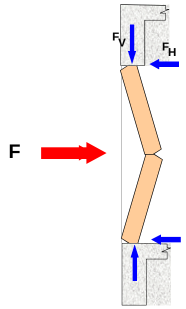
FLEXURAL STRENGTHENING OF URM WITH FRP SYSTEMS

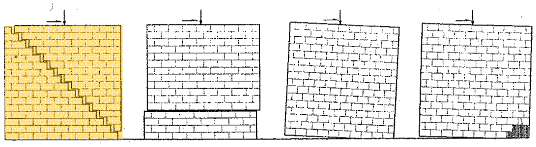
- FRP composite systems are very effective for strengthening of URM walls that can behave as simply-supported elements, or very nearly so
  - Including "stocky" walls provided that the walls are not built between rigid supports
- Walls with low h/t ratios (less than 12) and built between rigid supports can develop arching action
  - FRP not very effective
- Walls able to develop arching do not typically require to be strengthened, and therefore are not addressed by ACI 440.7R-10

What is Arching Action?



SHEAR STRENGTHENING OF URM WITH FRP SYSTEMS

- Walls under in-plane loads can have the following four modes of failure:
  - Diagonal tension (force-controlled failure)
  - Bed-joint sliding (force-controlled failure)
  - Toe crushing (force-controlled failure)
  - Rocking (deformation-controlled failure)



Diagonal Tension *Brittle Failure*

Bed-joint sliding *Brittle Failure*

Rocking *Ductile Failure*

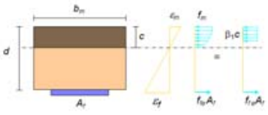
Toe crushing *Brittle Failure*

- Deformation-controlled failures are more ductile than force-controlled failures

FRP EFFECTIVE STRAINS AT ULTIMATE

- Flexural strength of URM wall strengthened with FRP

$$M_n = A_f f_{fe}\left(d_f - \frac{\beta_1 c}{2}\right)$$



$$f_{fe} = \kappa_m f_{fu}$$

FRP effective stress – f_{fe}?

- Shear strength of URM wall strengthened with FRP

$$V_n = V_m + V_f$$

$$V_f = \frac{A_f f_{fe} d_v}{s_f}$$

Steel : MSJC (ACI 530) $V_s = 0.5\frac{A_v f_y d_v}{s}$

FRP : $V_f = \frac{A_f(\kappa_v f_{fu})d_v}{s_f}$

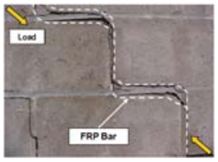
$$V_f = \kappa_v \frac{A_f f_{fu} d_v}{s_f}$$

FRP effective stress – f_{fe}?

FRP EFFECTIVE STRAINS AT ULTIMATE

- FRP debonding from the masonry substrate is the most common mode of failure
- For design purposes the strain in the FRP systems can be limited to prevent failure
- Express the effective strain ε_{fe} in the FRP system as:
  - $\varepsilon_{fe} = \kappa_m \varepsilon_{fu}$ for flexural strengthening
  - $\varepsilon_{fe} = \kappa_v \varepsilon_{fu}$ for shear strengthening

  where κ_m and κ_v are bond-dependent coefficients for flexure and shear



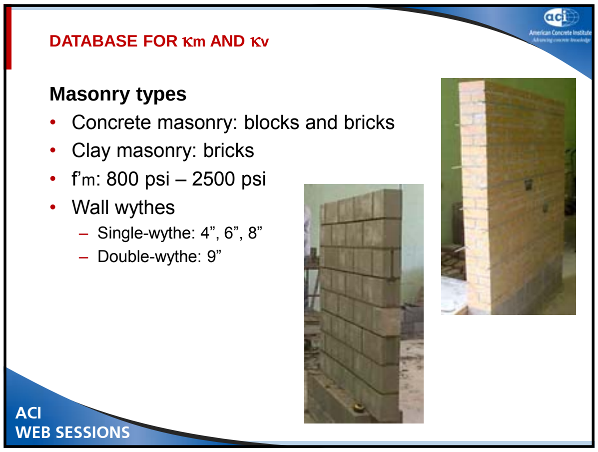
DATABASE FOR κm AND κv

Methodology

1. Collect test data available in the literature
   - Sources: US, Italy, UK, China, Chile
2. Analyze trends
3. Calibrate appropriate κm and κv values

Databases

- Flexural: FRP laminates and FRP bars (two databases)
- Shear: FRP laminates and FRP bars (two databases)
  - Only considered tests showing diagonal shear failure



DATABASE FOR κm AND κv

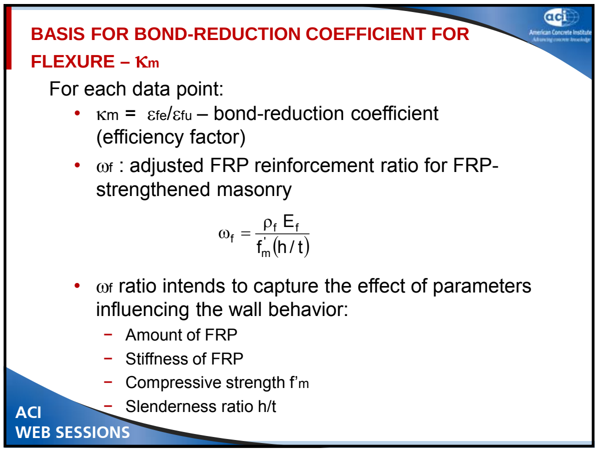
Masonry types

- Concrete masonry: blocks and bricks
- Clay masonry: bricks
- f'm: 800 psi – 2500 psi
- Wall wythes
  - Single-wythe: 4", 6", 8"
  - Double-wythe: 9"

DATABASE FOR κm AND κv

FRP Systems

- Laminates: CFRP, GFRP and AFRP
- Bars: CFRP and GFRP – round and rectangular
- FRP Shear Strengthening Layouts
  - One-side strengthening
  - Two-side strengthening
  - 0° and 45°



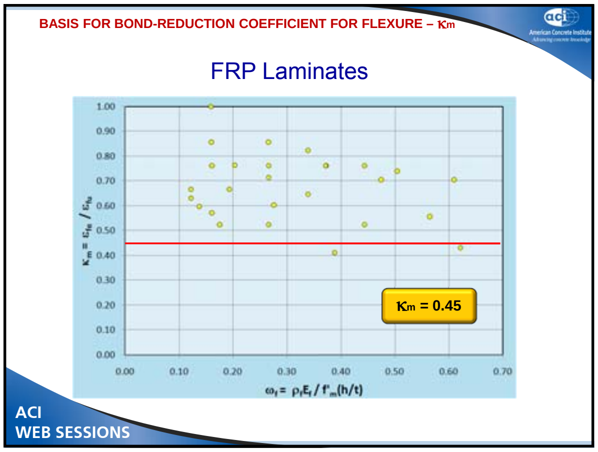
BASIS FOR BOND-REDUCTION COEFFICIENT FOR FLEXURE – κm

For each data point:

- κm = εfe/εfu – bond-reduction coefficient (efficiency factor)
- ωf : adjusted FRP reinforcement ratio for FRP-strengthened masonry

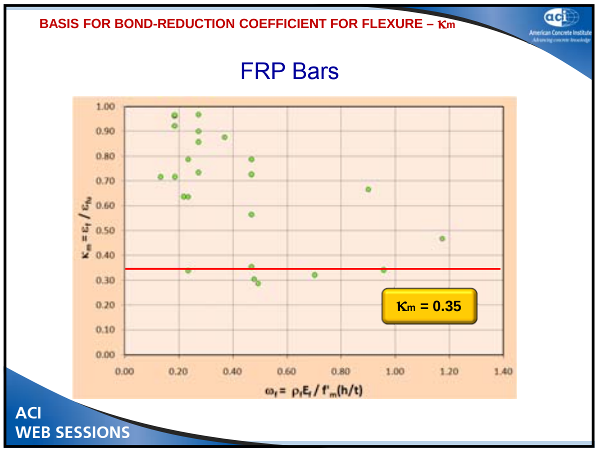
$$\omega_f = \frac{\rho_f E_f}{f'_m (h/t)}$$

- ωf ratio intends to capture the effect of parameters influencing the wall behavior:
  - Amount of FRP
  - Stiffness of FRP
  - Compressive strength f'm
  - Slenderness ratio h/t



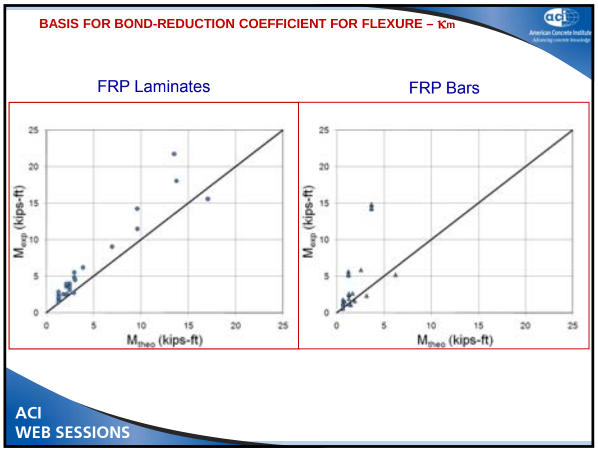
BASIS FOR BOND-REDUCTION COEFFICIENT FOR FLEXURE – κm

FRP Laminates



BASIS FOR BOND-REDUCTION COEFFICIENT FOR FLEXURE – κm

FRP Bars



BASIS FOR BOND-REDUCTION COEFFICIENT FOR FLEXURE – κm

FRP Laminates

FRP Bars

BASIS FOR BOND-REDUCTION COEFFICIENT FOR SHEAR – κv

For each data point:

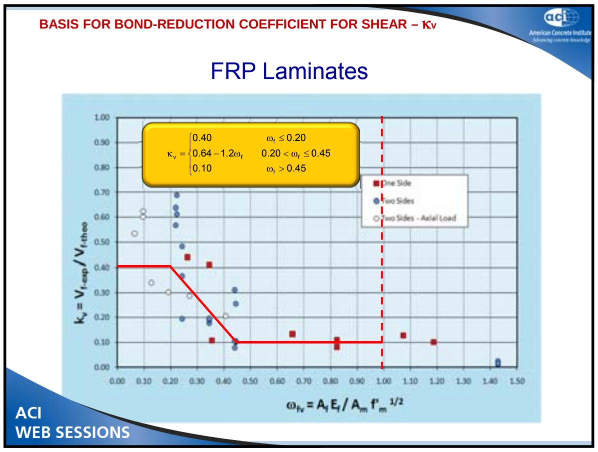
- $\kappa_v = V_{f\text{-}exp}/V_{f\text{-}fu}$ – bond-reduction coefficient (efficiency factor)
  - $V_{f\text{-}exp}$: experimental shear contribution of FRP
  - $V_{f\text{-}exp} = V_{u\text{-}exp} - V_{m\text{-}exp}$ ($V_{m\text{-}exp}$: URM control walls)
  - $V_{f\text{-}fu}$: max. FRP shear contribution – if premature failures do not occur

$$V_{f-fu} = \frac{A_f f_{fu} d_v}{s_f} \cos\alpha$$

- ω_{fv} – adjusted FRP reinforcement ratio for FRP-strengthened masonry

$$\omega_{fv} = \frac{A_f E_f}{A_m \sqrt{f'_m}}$$

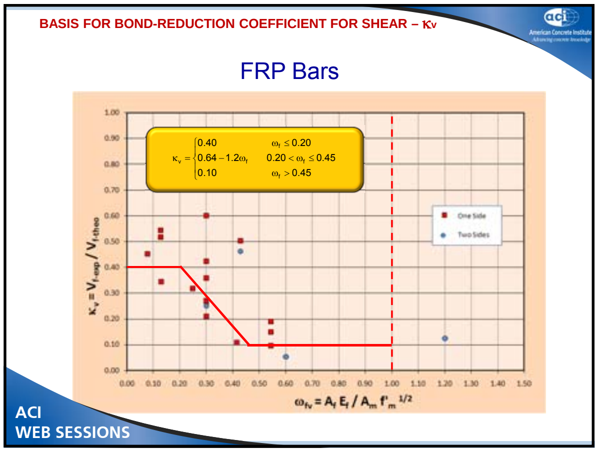
  - Recognize the relationship between the FRP strength and the masonry shear strength



BASIS FOR BOND-REDUCTION COEFFICIENT FOR SHEAR – κv

FRP Laminates

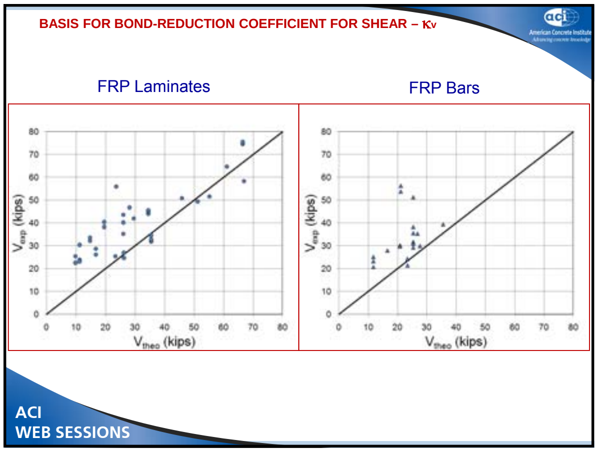
$$\kappa_v = \begin{cases} 0.40 & \omega_f \le 0.20 \\ 0.64 - 1.2\omega_f & 0.20 < \omega_f \le 0.45 \\ 0.10 & \omega_f > 0.45 \end{cases}$$



BASIS FOR BOND-REDUCTION COEFFICIENT FOR SHEAR – κv

FRP Bars

$$\kappa_v = \begin{cases} 0.40 & \omega_f \le 0.20 \\ 0.64 - 1.2\omega_f & 0.20 < \omega_f \le 0.45 \\ 0.10 & \omega_f > 0.45 \end{cases}$$



BASIS FOR BOND-REDUCTION COEFFICIENT FOR SHEAR – κv

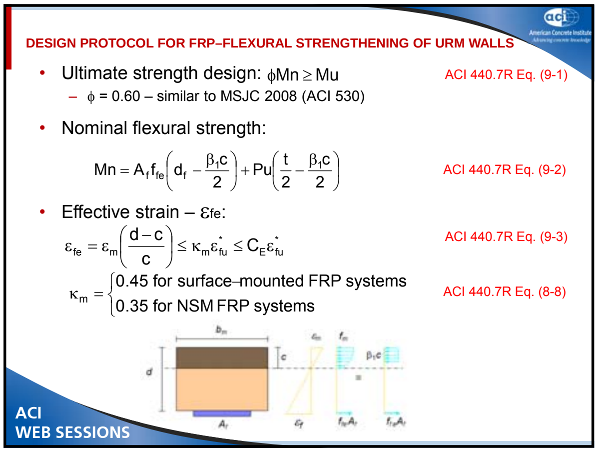
FRP Laminates

FRP Bars

DESIGN PROTOCOL FOR FRP–FLEXURAL STRENGTHENING OF URM WALLS

Design Assumptions:

- Strains in the FRP and masonry are directly proportional to their distance from the neutral axis
- The maximum usable compressive strain:
  - 0.0025 for concrete masonry
  - 0.0035 for clay masonry
- FRP reinforcement is linear elastic up to failure
- Contribution of masonry in tension and FRP reinforcement in compression is neglected
- No relative slip between the FRP reinforcement and masonry until debonding failure occurs; and
- Wall behaves as a simply-supported element or very nearly so
  - i.e. arching mechanism does not develop



DESIGN PROTOCOL FOR FRP–FLEXURAL STRENGTHENING OF URM WALLS

- Ultimate strength design: $\phi Mn \ge Mu$ ACI 440.7R Eq. (9-1)
  - ϕ = 0.60 – similar to MSJC 2008 (ACI 530)
- Nominal flexural strength:

$$Mn = A_f f_{fe}\left(d_f - \frac{\beta_1 c}{2}\right) + Pu\left(\frac{t}{2} - \frac{\beta_1 c}{2}\right)$$ ACI 440.7R Eq. (9-2)

- Effective strain – ε_{fe}:

$$\varepsilon_{fe} = \varepsilon_m\left(\frac{d-c}{c}\right) \le \kappa_m \varepsilon^*_{fu} \le C_E \varepsilon^*_{fu}$$ ACI 440.7R Eq. (9-3)

$$\kappa_m = \begin{cases} 0.45 \text{ for surface–mounted FRP systems} \\ 0.35 \text{ for NSM FRP systems} \end{cases}$$ ACI 440.7R Eq. (8-8)

DESIGN PROTOCOL FOR FRP–FLEXURAL STRENGTHENING OF URM WALLS

- Effective strain: $\varepsilon_{fe} = \varepsilon_m \left(\frac{d-c}{c} \right) \le \kappa_m \varepsilon_{fu}^* \le C_E \varepsilon_{fu}^*$

$$\kappa_m = \begin{cases} 0.45 \text{ for surface–mounted FRP systems} \\ 0.35 \text{ for NSM FRP systems} \end{cases}$$

- κm coefficients control over the CE coefficients
- Use of larger κm if properly substantiated by testing

ACI 440.7R Table 8.1 – Environmental reduction factors

Exposure conditions	Fiber Type	CE
Interior exposure (partitions)	Carbon	0.95
	Glass	0.75
	Aramid	0.85
Exterior exposure (exterior walls, including internal side of exterior walls)	Carbon	0.85
	Glass	0.65
	Aramid	0.75
Aggressive environment (basement walls)	Carbon	0.85
	Glass	0.50
	Aramid	0.70

DESIGN PROTOCOL FOR FRP–FLEXURAL STRENGTHENING OF URM WALLS

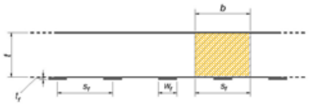
Limitations:

- Walls with h/t larger than 20 should not be strengthened with FRP unless the efficiency of FRP has been properly substantiated by testing
  - Limitation based on the h/t ratios included in the database
  - Risk of very slender walls to become unstable due to out-of-plane loads and secondary bending moments caused by axial loads when walls deform
- Walls with h/t smaller than 8 and built within stiff supports should not be strengthened with FRP
  - Most likely do not require to be strengthened because of arching mechanism
  - Marginal increases in flexural capacities

DESIGN PROTOCOL FOR FRP–FLEXURAL STRENGTHENING OF URM WALLS

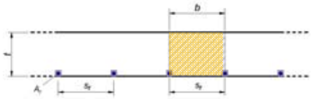
Spacing for FRP flexural strengthening

- FRP Laminates



$s_{f,max} \le 3t + w_f$

- FRP Bars



$s_{f,max} \le 3t$

DESIGN PROTOCOL FOR FRP–SHEAR STRENGTHENING OF URM WALLS

- Ultimate strength design: $\phi Vn \ge Vu$ ACI 440.7R Eq. (10-2)
  - ϕ = 0.80 – similar to MSJC 2008 (ACI 530)
- Nominal shear strength:

$$Vn = Vm^{URM} + Vf$$ ACI 440.7R Eq. (10-3)

Vm^{URM}: shear strength of URM wall (estimated following recommendations provided by MSJC or ASCE-41)

$$Vf = \begin{cases} \rho_{fv} w_f \frac{d_v}{s_f} \text{ for surface–mounted FRP systems} \\ \rho_{fv} \frac{d_v}{s_f} \text{ for NSM FRP systems} \end{cases}$$ ACI 440.7R Eq. (10-4)

$$\rho_{fv} = \begin{cases} n t_f f_{fe} \le 1500 \text{ lb/in. for surface–mounted FRP systems} \\ A_{f,bar} f_{fe} \le 10{,}000 \text{ lb/bar for NSM FRP systems} \end{cases}$$ ACI 440.7R Eq. (8-14)

DESIGN PROTOCOL FOR FRP–SHEAR STRENGTHENING OF URM WALLS

- Effective strain: $\varepsilon_{fe} = \kappa_v \varepsilon_{fu}^* \le C_E \varepsilon_{fu}^*$ ACI 440.7R Eq. (8-10)

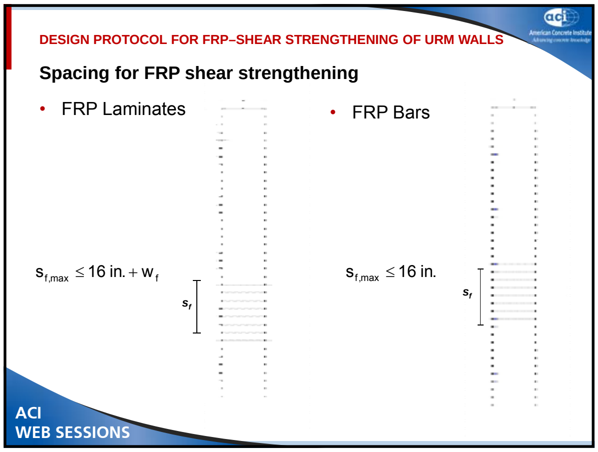
$$\omega_{fv} = \frac{A_f E_f}{A_m \sqrt{f_m'}} \qquad \kappa_v = \begin{cases} 0.40 \text{ for } \omega_f \le 0.20 \\ 0.64 - 1.2\omega_f \text{ for } 0.20 < \omega_f \le 0.45 \\ 0.10 \text{ for } \omega_f > 0.45 \end{cases}$$ ACI 440.7R Eq. (8-13)

- κv coefficients control over the CE coefficients
- Use of larger κv if properly substantiated by testing

DESIGN PROTOCOL FOR FRP–SHEAR STRENGTHENING OF URM WALLS

Limitations: ACI 440.7R Table 10.1

Masonry Type	Wall Construction	FRP Strengthening Layout
Hollow unit masonry wall	t = 8 in. or less Ungrouted or partially grouted walls with grouted cells spaced greater than 48 in.	FRP on one face of wall is acceptable
	t = 8 in. or less Fully grouted or partially grouted walls with grouted cells spaced at 48 in. or less	FRP on two faces of wall is required
	t = 10 to 12 in. Ungrouted or partially grouted walls with grouted cells spaced greater than 60 in.	FRP on two faces of wall is required
	t = 10 to 12 in. Fully grouted or partially grouted walls with grouted cells spaced at 60 in. or less	Use of FRP is not recommended
	t greater than 12 in. Ungrouted or grouted	Use of FRP is not recommended
Solid unit masonry wall	Single-wythe walls with t = 4 in. or less	FRP on one face of wall is acceptable
	Double-wythe walls with t = 8 in. or less	FRP on two faces of wall is required
	Multi-wythe walls with t > 8 in.	Use of FRP is not recommended



DESIGN PROTOCOL FOR FRP–SHEAR STRENGTHENING OF URM WALLS

Spacing for FRP shear strengthening

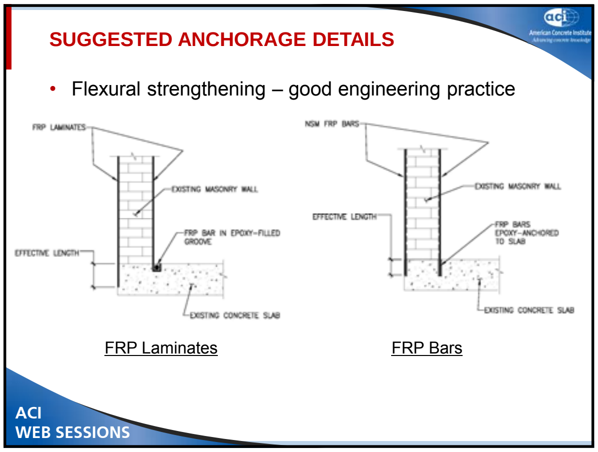
- FRP Laminates
- FRP Bars

$s_{f,max} \le 16\text{ in.} + w_f$

s_f

$s_{f,max} \le 16\text{ in.}$

s_f

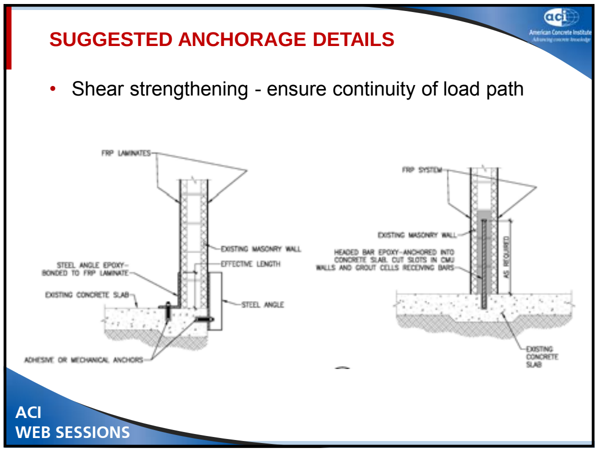


SUGGESTED ANCHORAGE DETAILS

- Flexural strengthening – good engineering practice

FRP Laminates

FRP Bars



SUGGESTED ANCHORAGE DETAILS

- Shear strengthening - ensure continuity of load path

FINAL REMARKS

- It is expected that strengthening of masonry with FRP systems will become more common with the availability of ACI guides
- Future work of ACI Sub-Committee 440M:
  - Refine κm and κv values as more research results become available
  - Develop design recommendations for shear strengthening of infill walls

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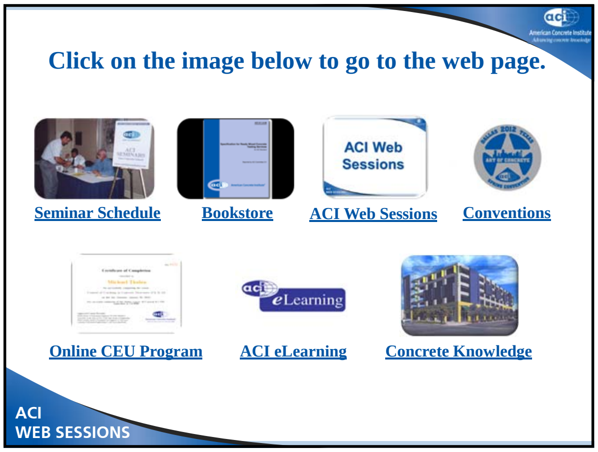

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