New Strengthening System for Concrete and Masonry

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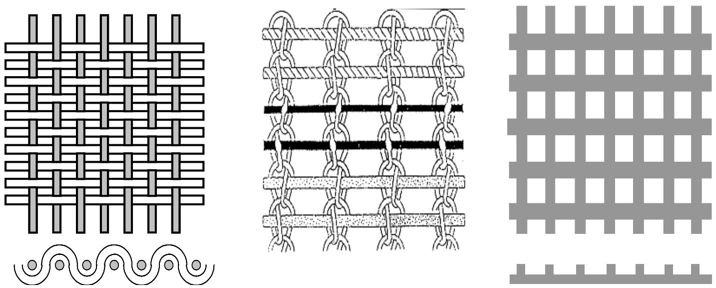
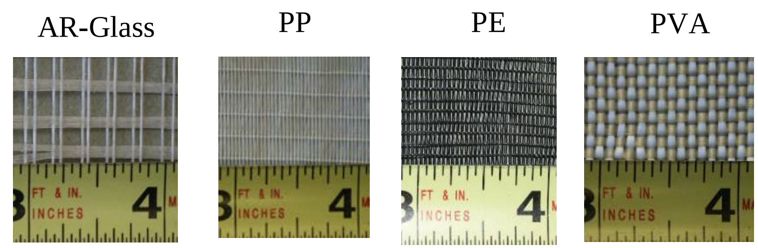
1 FRCM CHARACTERIZATION – A) Material systems, B) concrete strengthening (slabs, beams and columns), and C) clay and CMU masonry strengthening (in-plane and out-of-plane)

Two key components of FRCM are cementitious matrix (grout system based on cement and low dosage of dry organic polymers) and fiber network. Organic polymers as additives necessary to ensure proper workability, setting time, and mechanical properties of matrix





Mechanical effectiveness of FRCM strongly influenced by ability of cementitious matrix to “wet” dry fiber strands, bond between the matrix and fibers, and bond between matrix and substrate

1

FRCM composites identified with several terms: Textile-reinforced concrete (TRC); textile-reinforced mortar (TRM), mineral-based composites (MBC), and fiber-reinforced cement (FRC)

Characterization – Material Systems

1

PBO (Polyparaphenylene benzobisoxazole) mesh in a stabilized inorganic matrix

Carbon mesh and a special mortar based on pozzolan cement

Cont. – Characterization – Tensile Specimens Preparation

First layer of mortar

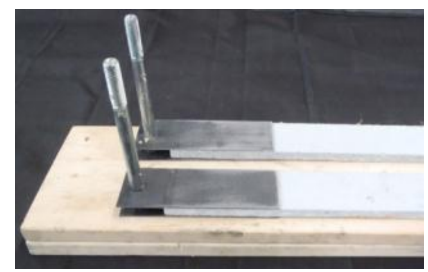
Impregnate mesh

Place mesh

1

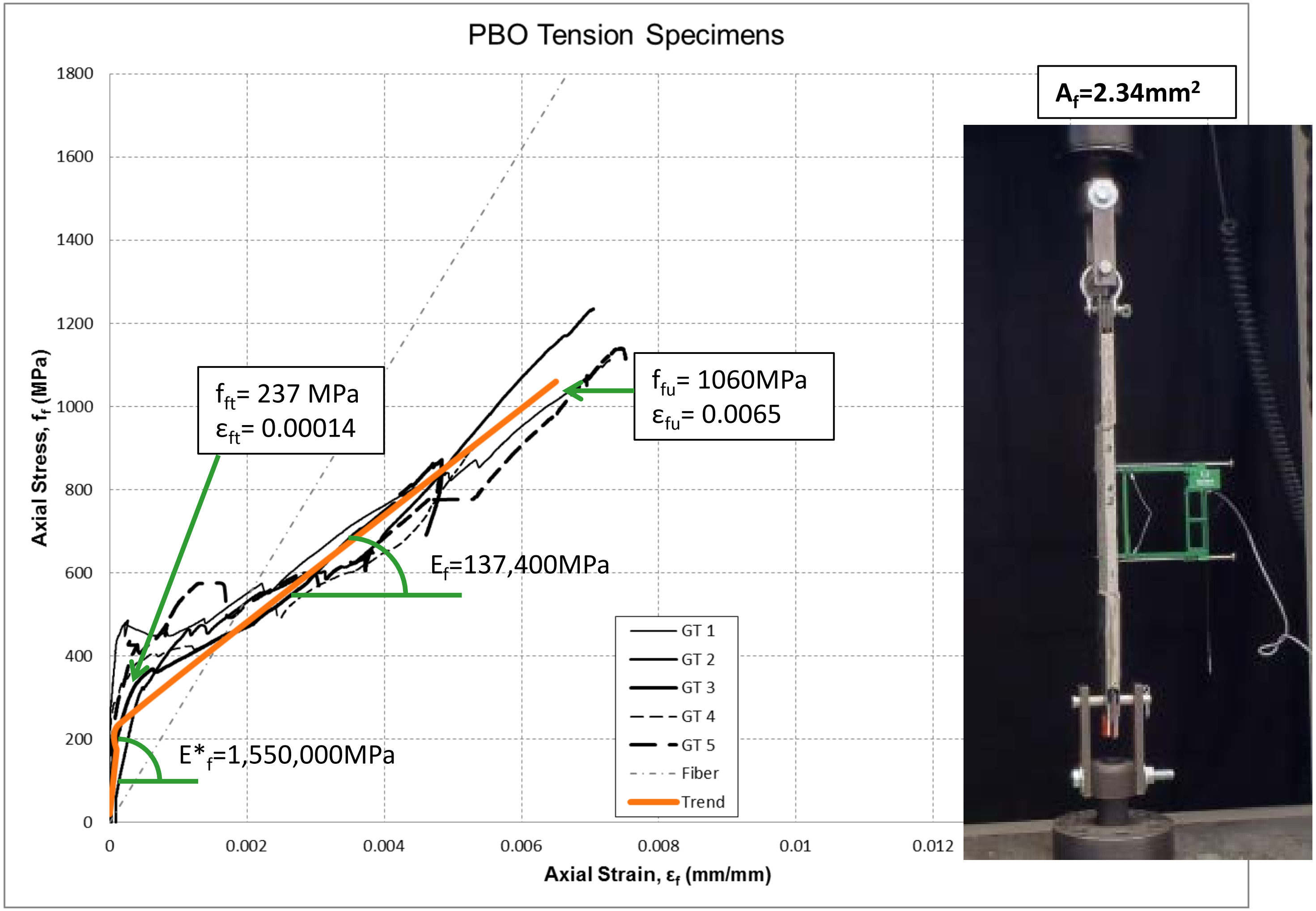
Cure for 28 days

Cut coupons



Align and glue metal tabs

Cont. – Characterization – Typical Tensile Properties



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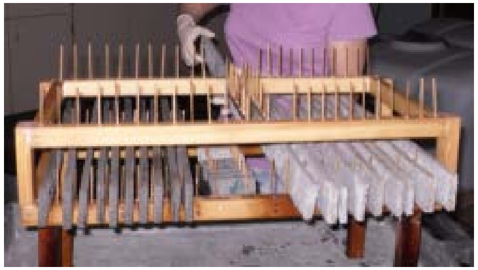
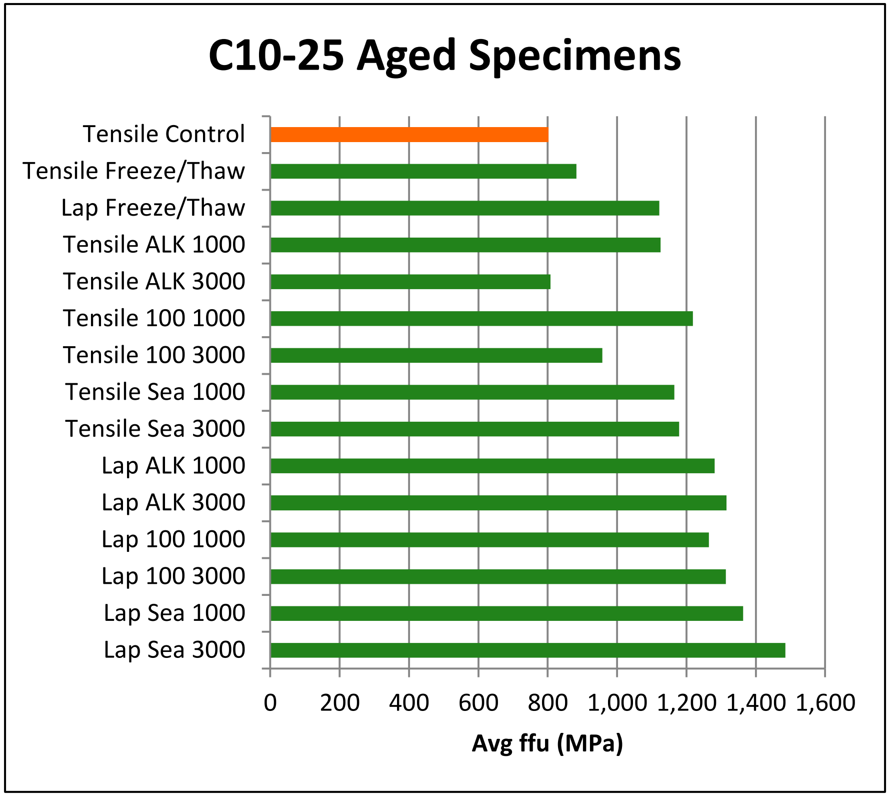
Cont. – Characterization – Durability Results





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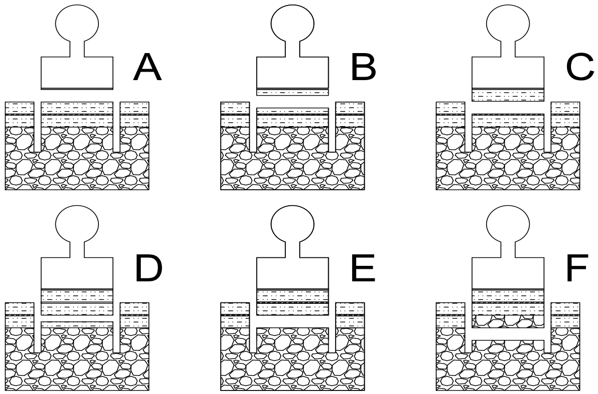
Cont. – Characterization – Bond Tests



Possible Failure Modes

Specimen ID	Failure Mode
Concrete Substrate 1	C
Concrete Substrate 2	C
Concrete Substrate 3	E
Concrete Substrate 4	C
Concrete Substrate 5	C
Concrete Substrate 6	C
Concrete Substrate 7	E
Concrete Substrate 8	C

Typical Failure Mode

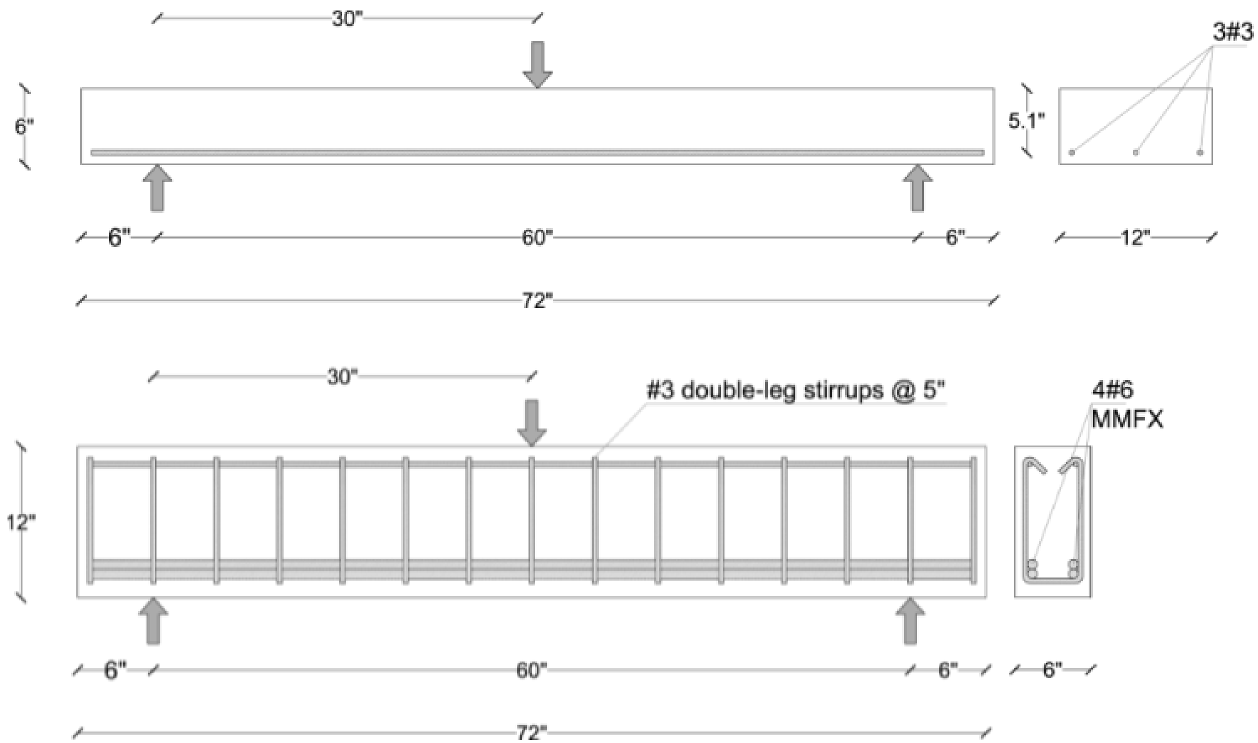
Specimen ID	Failure Mode
Concrete Block (CMU) 1	C
Concrete Block (CMU) 2	C
Concrete Block (CMU) 3	C
Cocnrete Block (CMU) 4	C
Concrete Block (CMU) 5	C
Concrete Block (CMU) 6	C
Concrete Block (CMU) 7	C
Concrete Block (CMU) 8	C
Concrete Block (CMU) 9	C
Concrete Block (CMU) 10	F

1

Unlike FRP, FRCM fibers are dry and effectively reduce the area of mortar that is loaded, resulting in a reduced "net area"

Cont. – Characterization –Beams and Slabs

- Amount and type of longitudinal steel reinforcement are selected in order to induce the FRCM failure
- Extremes of FRCM reinforcement are considered: 1 ply and 4 plies
- Extremes of concrete strength are considered: 3,500-psi and 7,000-psi concrete
- Three repetitions. 18 Slabs, 18 Flexure Beams



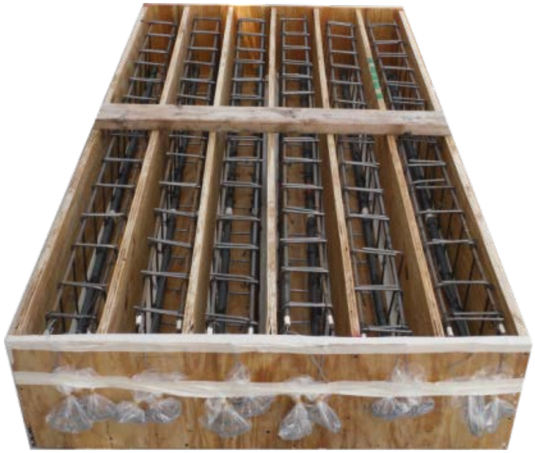
SLAB

FLEX BEAM

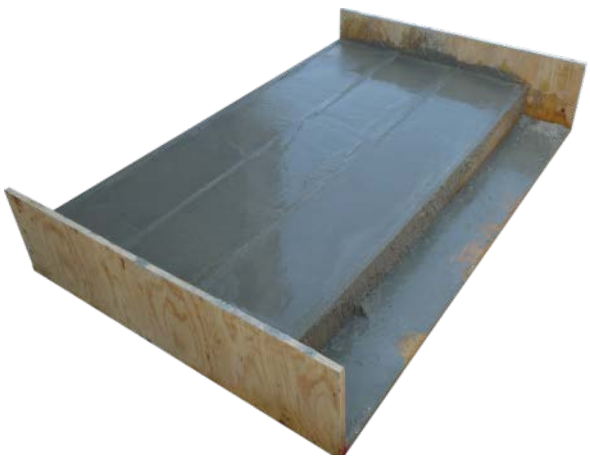
1

Cont. – Characterization – Specimens Preparation

1



FORMWORK

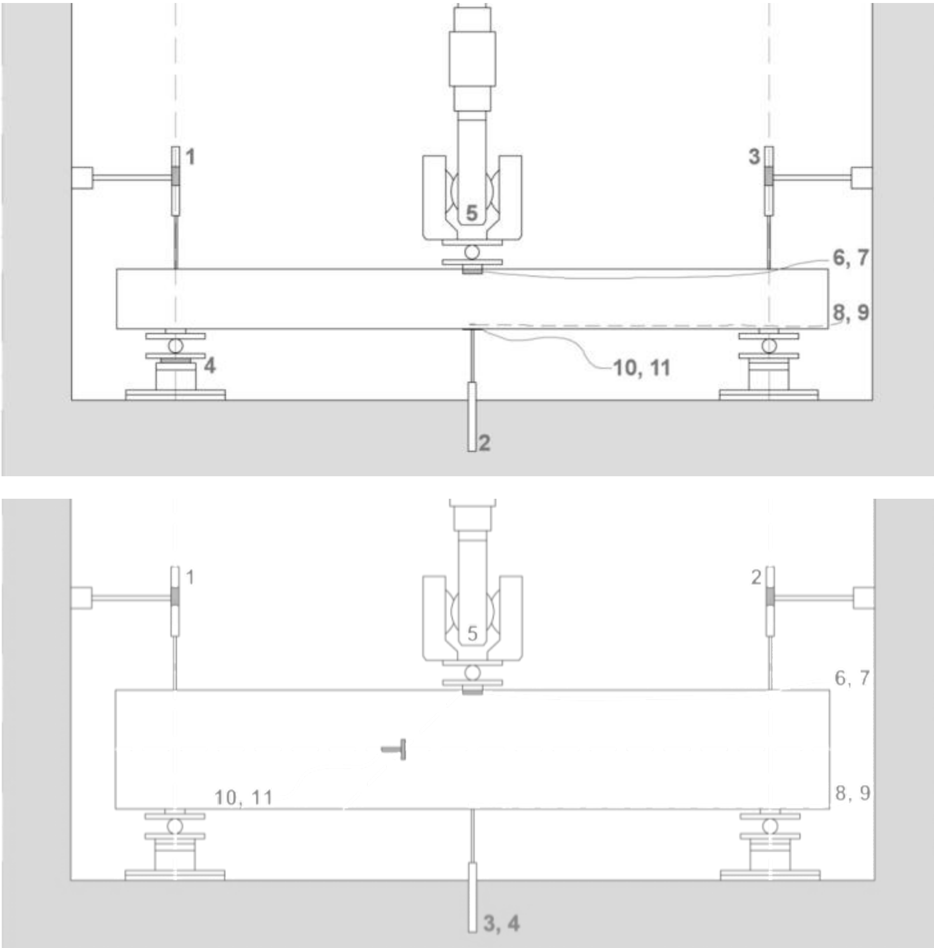


CASTING

FRCM INSTALLATION

Cont. – Characterization – Test Setup

1



1-3) LVDTs; 4-5) Load Cells; 6-7) Concrete strain gauges;
8-9) Steel strain gauge; 10-11) FRCM Strain gauges

Cont. – Characterization – Results (Slabs and Beams in Flexure – Low and High Strength Concrete)

SLABS

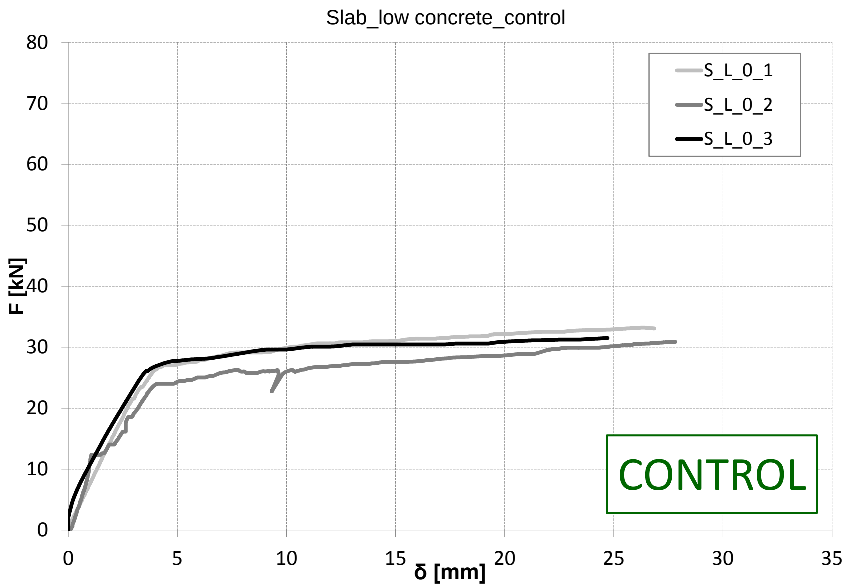
Specimen ID	Exp. Average $M_{u,avg}$ kip·ft	Exp. Strength Enhancement $M_{u,avg,s}$/ $M_{u,avg,c}$ -	Theoretical (Th.) Design Criteria $M_{u,Th}$ kip·ft	Th. Strenght Enhancement $M_{u,Th,s}$ / $M_{u,Th,c}$ -	Exp./Th. Ratio $M_{u,avg}/M_{u,Th}$ -
S_L_0_X	8.95	1.00	8.00	1.00	1.12
S_L_1_X	12.65	1.41	8.89	1.11	1.42
S_L_4_X	18.35	2.05	12.01	1.50	1.53
S_H_0_X	8.71	1.00	8.13	1.00	1.07
S_H_1_X	11.80	1.35	8.98	1.10	1.31
S_H_4_X	18.48	2.12	12.15	1.50	1.52

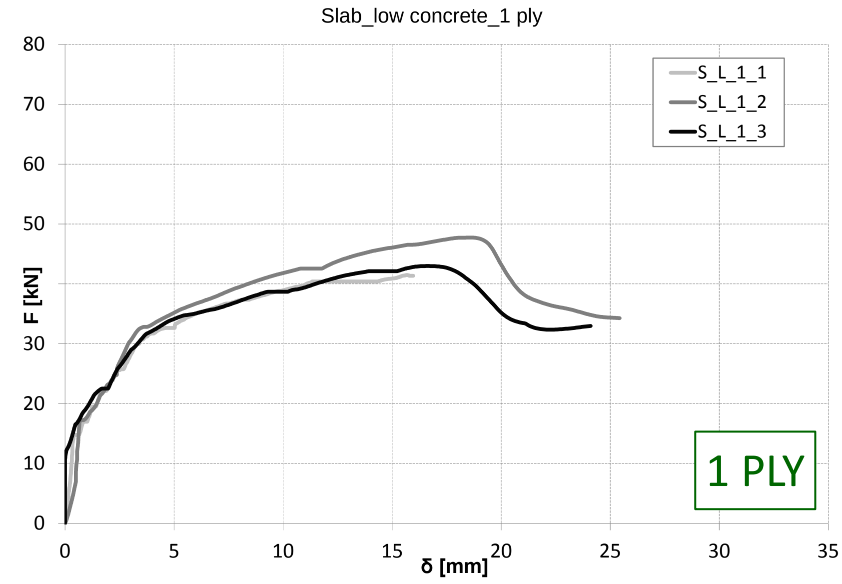
BEAMS

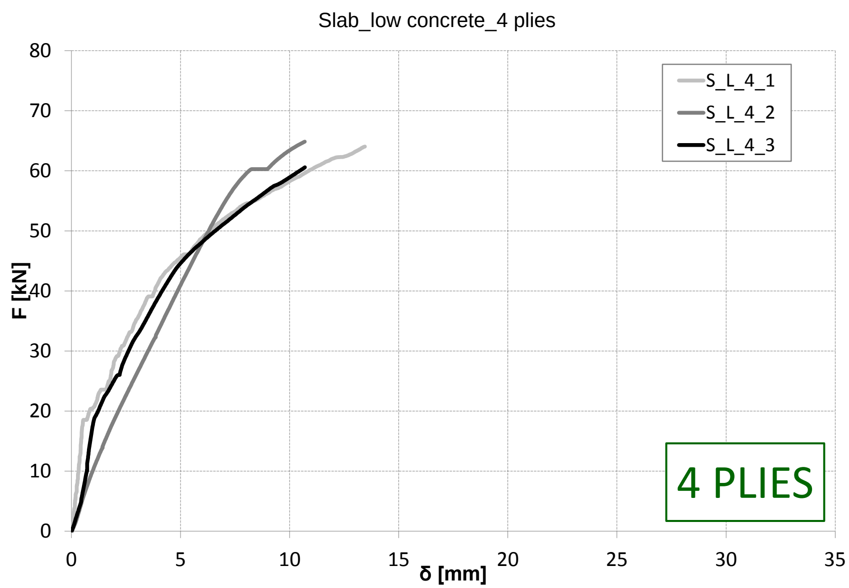
Specimen ID	Exp. Average $M_{u,avg}$ kip·ft	Exp. Strength Enhancement $M_{u,avg,s}$/ $M_{u,avg,c}$ -	Theoretical (Th.) Design Criteria $M_{u,Th}$ kip·ft	Th. Strenght Enhancement $M_{u,Th,s}$ / $M_{u,Th,c}$ -	Exp./Th. Ratio $M_{u,avg}/M_{u,Th}$ -
B_L_0_X	14.45	1.00	12.94	1.00	1.12
B_L_1_X	19.03	1.32	13.73	1.06	1.39
B_L_4_X	27.83	1.93	16.91	1.31	1.65
B_H_0_X	15.69	1.00	13.08	1.00	1.20
B_H_4_X	17.71	1.13	13.83	1.06	1.28
B_H_1_X	27.21	1.73	17.05	1.30	1.60

X is the average of 3 repetitions

Cont. – Characterization – Results (Slabs in Flexure – Low Strength Concrete)

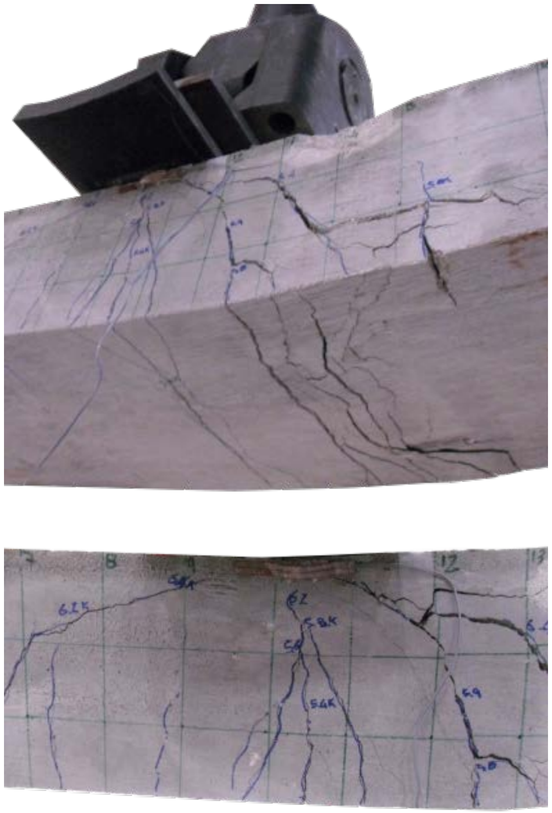




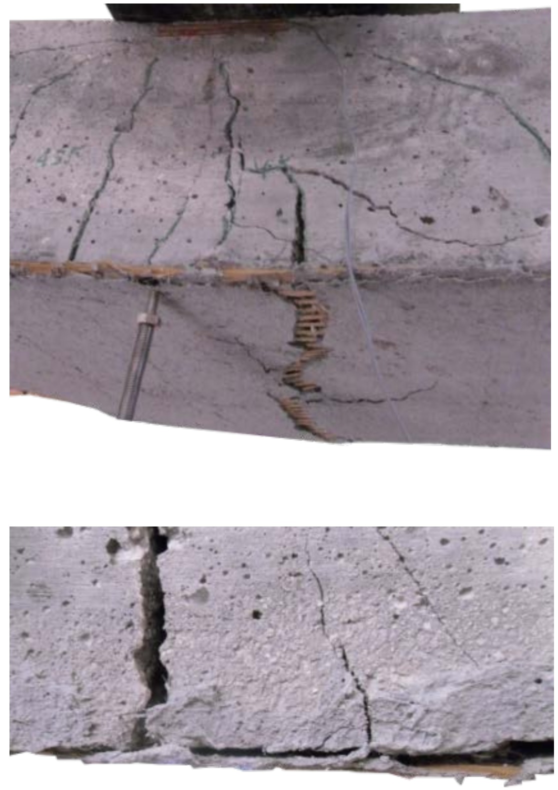


Cont. – Characterization – Failure Mode

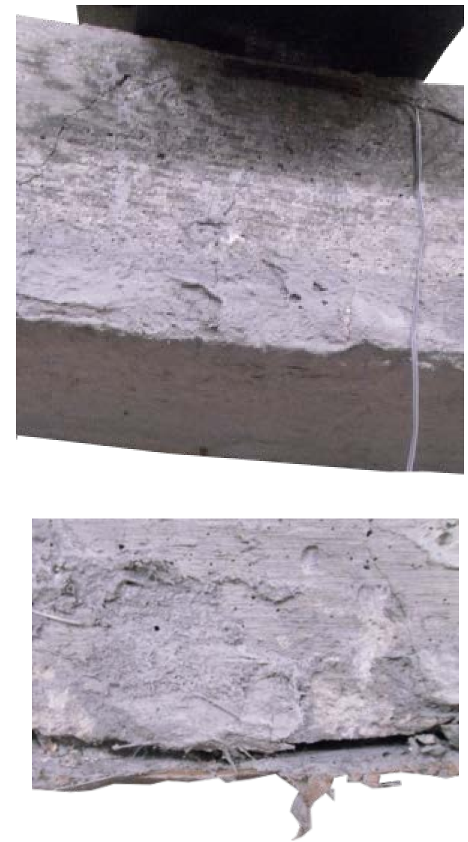
1



CONTROL



1PLY

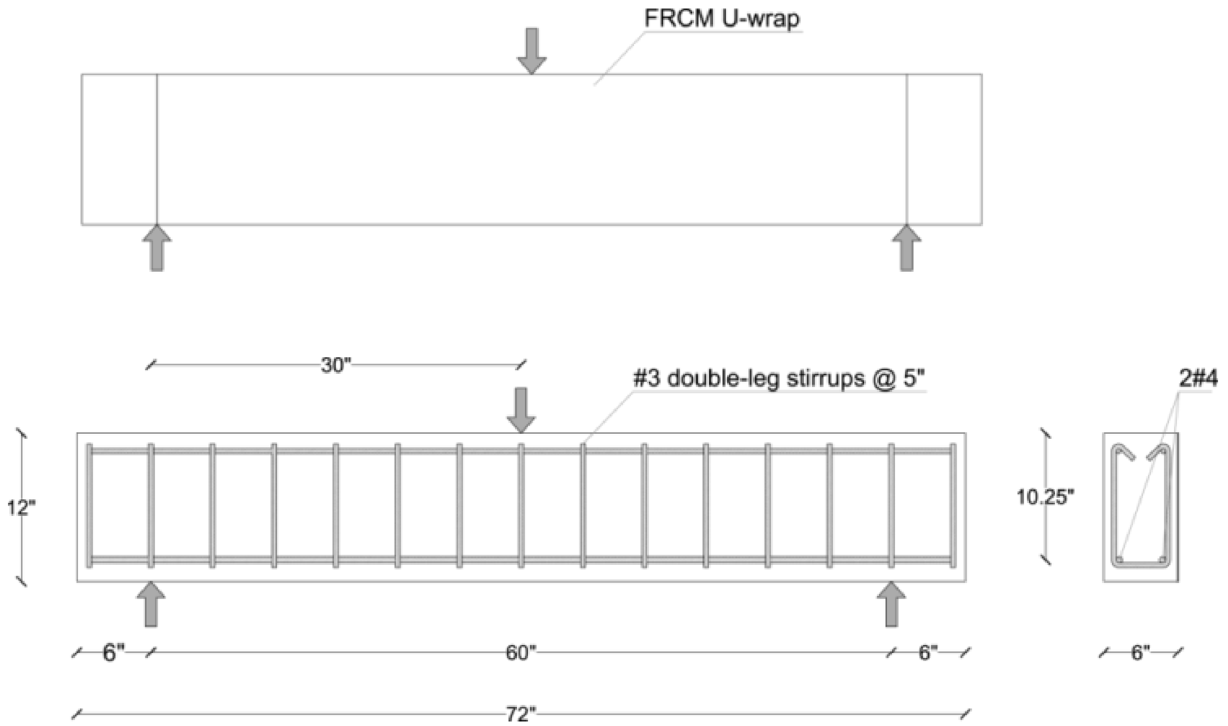


4PLIES

Cont. – Characterization –Beams and Slabs

- Extremes of FRCM reinforcement are considered: 1 ply and 4 plies.
- Extremes of concrete strength are considered: 3,500-psi and 7,000-psi concrete.
- Three repetitions. 18 Shear Beams.

SHEAR BEAM



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Cont. – Characterization – Results (Shear – Low and High Strength Concrete)

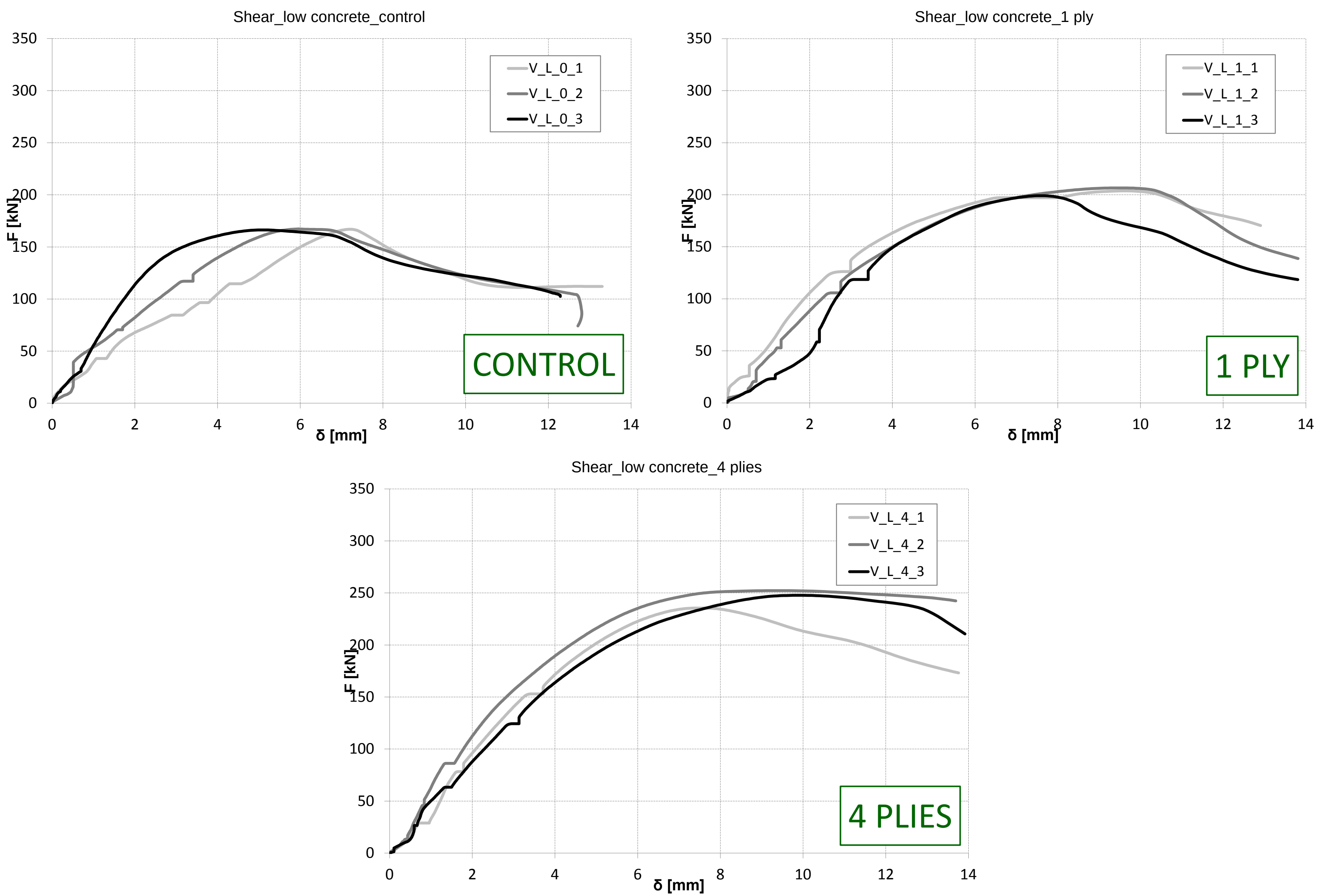
1

SHEAR

Specimen ID	Exp. Average $M_{u,avg}$ kip·ft	Exp. Strength Enhancement $M_{u,avg,s}$/ $M_{u,avg,c}$ -	Theoretical (Th.) Design Criteria $M_{u,Th}$ kip·ft	Th. Strenght Enhancement $M_{u,Th,s}$ / $M_{u,Th,c}$ -	Exp./Th. Ratio $M_{u,avg}/M_{u,Th}$ -
V_L_0_X	46.89	1.00	34.46	1.00	1.36
V_L_1_X	57.09	1.22	38.76	1.12	1.47
V_L_4_X	68.89	1.47	51.69	1.50	1.33
V_H_0_X	51.50	1.00	38.16	1.00	1.35
V_H_1_X	64.96	1.26	42.48	1.11	1.53
V_H_4_X	83.09	1.61	55.39	1.45	1.50

X is the average of 3 repetitions

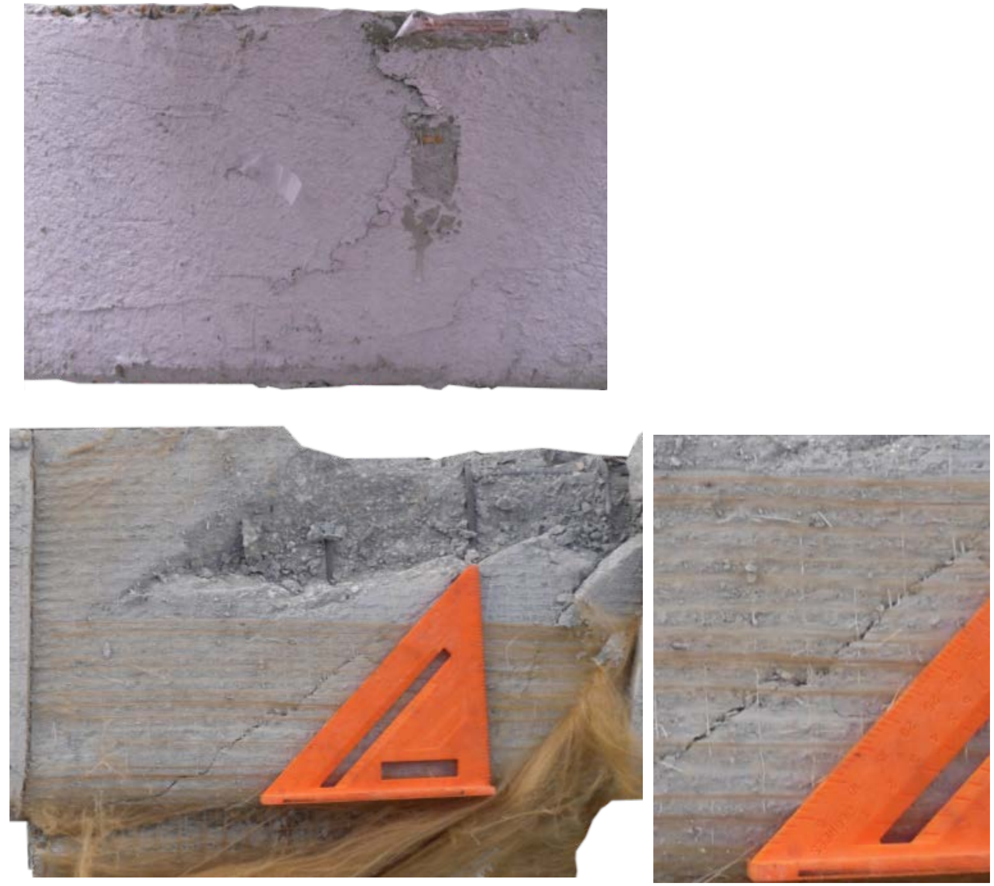
Cont. – Characterization – Results (Shear – Low Strength Concrete)



Cont. – Characterization – Failure Mode

1

1PLY

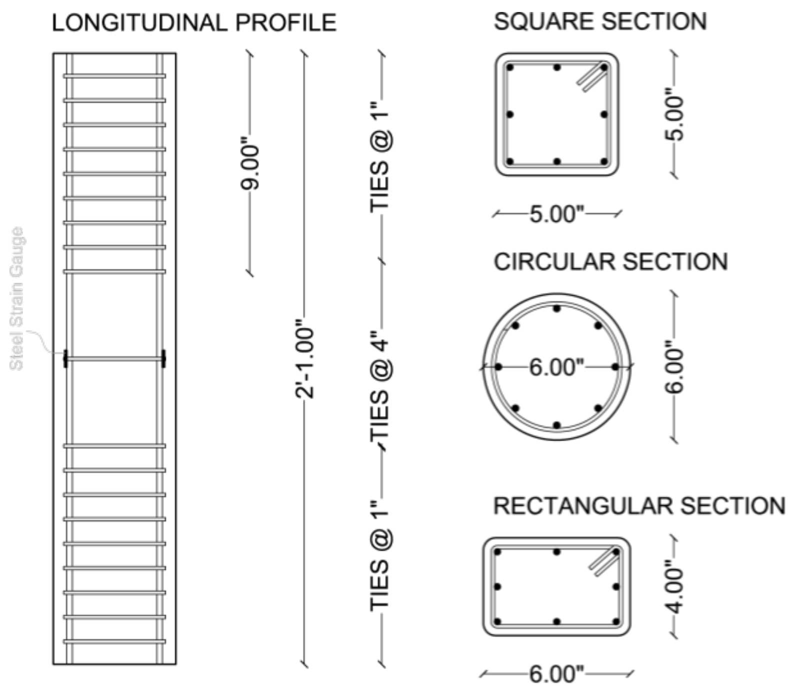


4PLIES

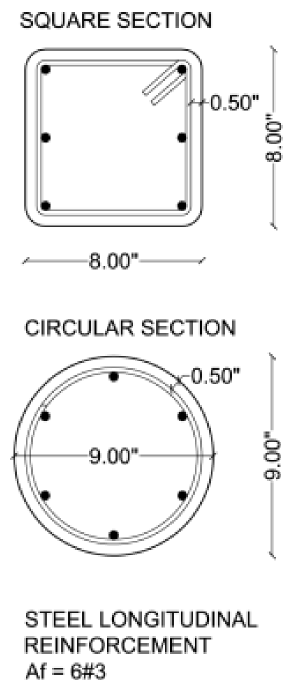
Cont. – Characterization – Columns

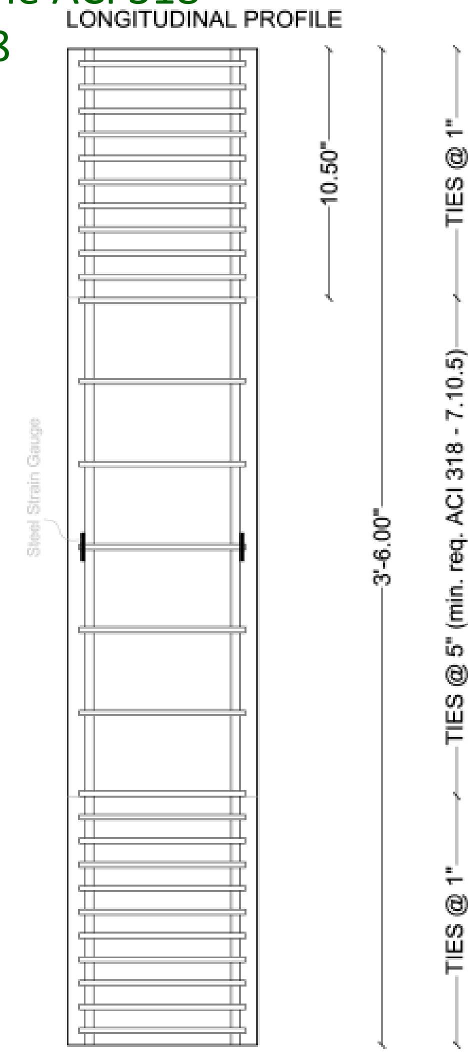
- 2 different scales (1-to-3 and 1-to-5)
- Minimum amount of longitudinal steel reinforcement by the ACI 318
- Minimum size and maximum spacing of ties by the ACI 318
- Extremes of concrete : 3,500-psi and 7,000-psi concrete
- Extremes of FRCM: 1 ply and 4 plies of U-wrap
- Total: 18 large scale; 27 small scale

1



SMALL-SCALE COLUMNS





LARGE-SCALE COLUMNS

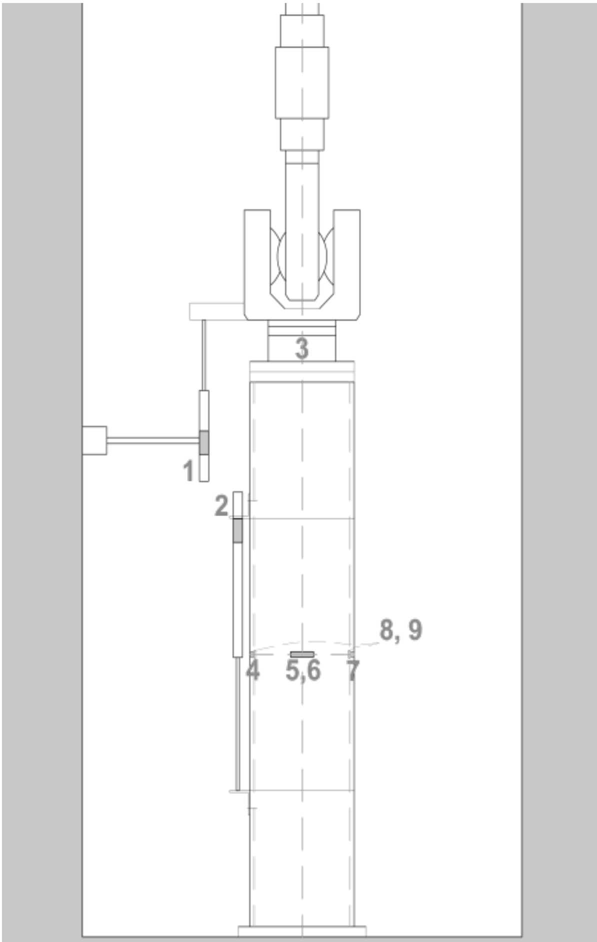
Cont. – Characterization – Specimens Preparation

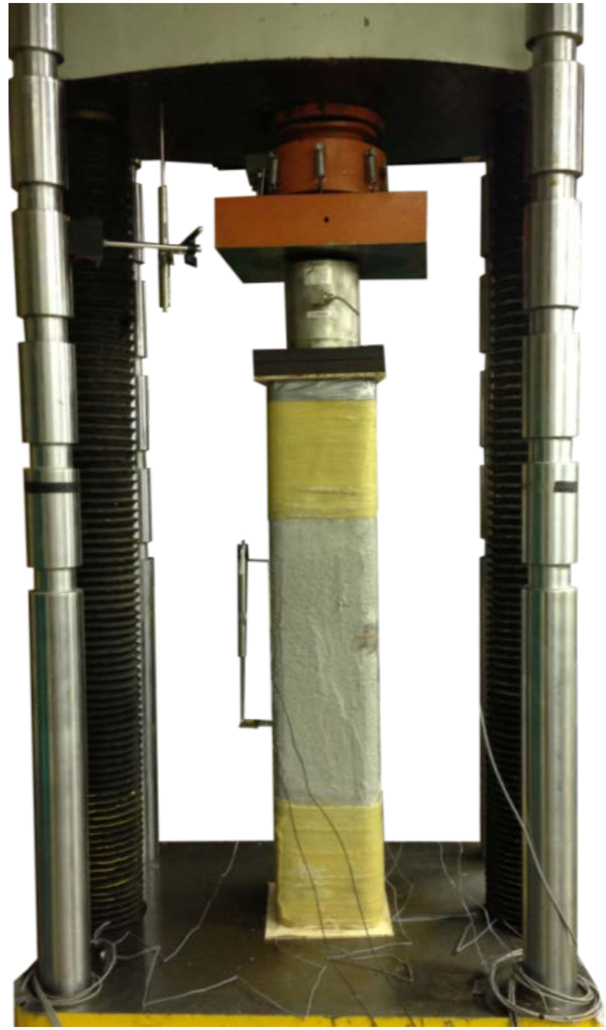
CASTING

FRCM INSTALLATION

1

Cont. – Characterization – Test Set up





LOAD CELL

SETTLEMENT

1-2) LVDTs; 3) Load cell
4-7) Concrete strain gages
8-9) Steel strain gauges

1

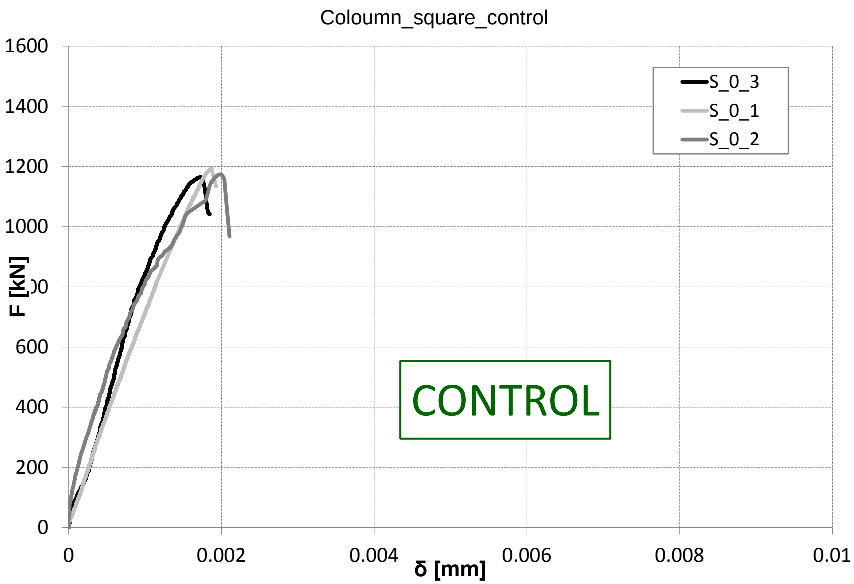
LARGE SCALE COLUMNS

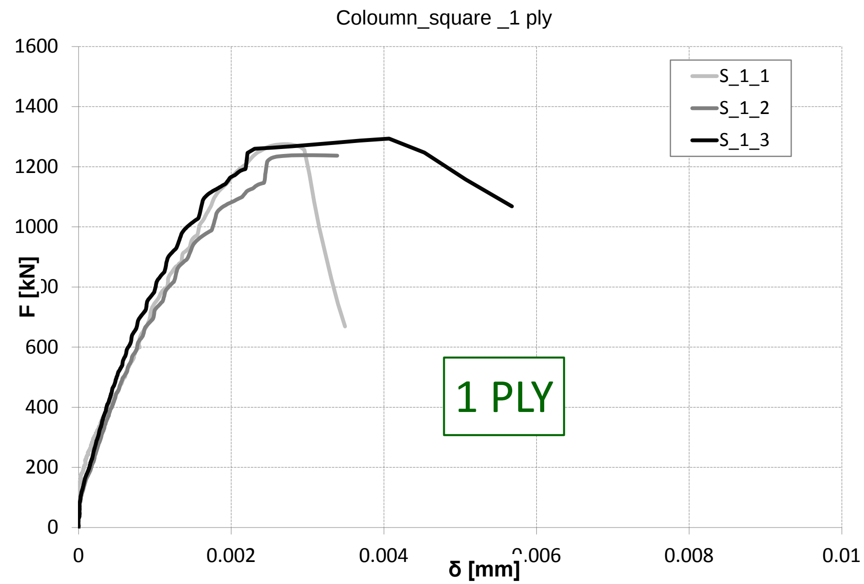
Specimen ID	Exp. Average $P_{u,avg}$ kip	Exp. Strength Enhancement $P_{u,avg,strengthed}$ / $P_{u,avg,control}$ -	Theoretical (Th.) Design Criteria $P_{u,Th}$ kip	Th. Strenght Enhancement $P_{u,Th,strengthed}$ / $P_{u,Th,control}$ -	Exp./Th. Ratio $P_{u,avg}/P_{u,Th}$ -
L_C_0_X	233	1.00	207	1.00	1.13
L_C_1_X	257	1.10	212	1.02	1.21
L_C_4_X	307	1.32	230	1.11	1.33
L_S_0_X	264	1.00	219	1.00	1.21
L_S_1_X	285	1.08	222	1.01	1.28
L_S_4_X	326	1.23	231	1.05	1.41

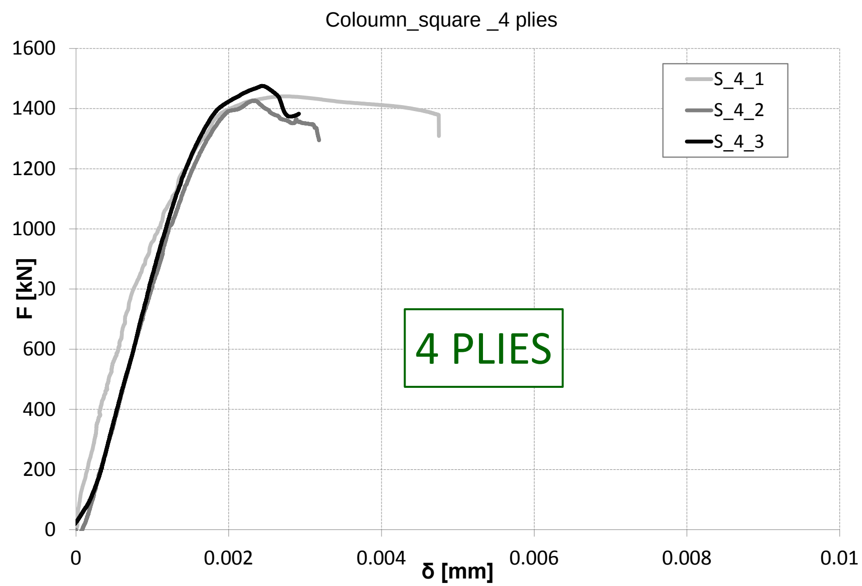
1

X is the average of 3 repetitions

Cont. – Characterization – Results for square columns







Cont. – Characterization – Failure Mode

1

BULGING

SLIPPAGE

DELAMINATION

BUCKLING

Cont. – Characterization – CMU and clay masonry

Erecting walls

Installing FRCM

Curing FRCM

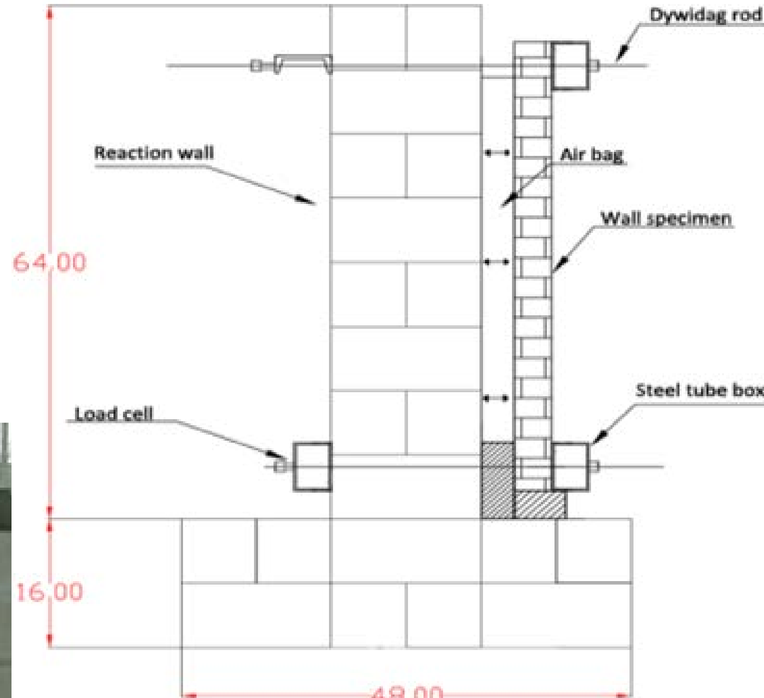
1

Test matrix (Out-of-Plane loading tests)

Specimen Code	Strengthening Material	Masonry Type	Repetition
O-CMU-Control	None	Concrete Block	3
O-CMU-1Ply	1 Ply of FRCM	Concrete Block	3
O-CMU-4Ply	4 Ply of FRCM	Concrete Block	3
O-CL-Control	None	Clay Brick	3
O-CL-1Ply	1 Ply of FRCM	Clay Brick	3
O-CL-4Ply	4 Ply of FRCM	Clay Brick	3

1

Cont. – Characterization – Test Set up (Out-of-Plane Loading Test)



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CMU-control wall

CMU wall with 4-ply FRCM

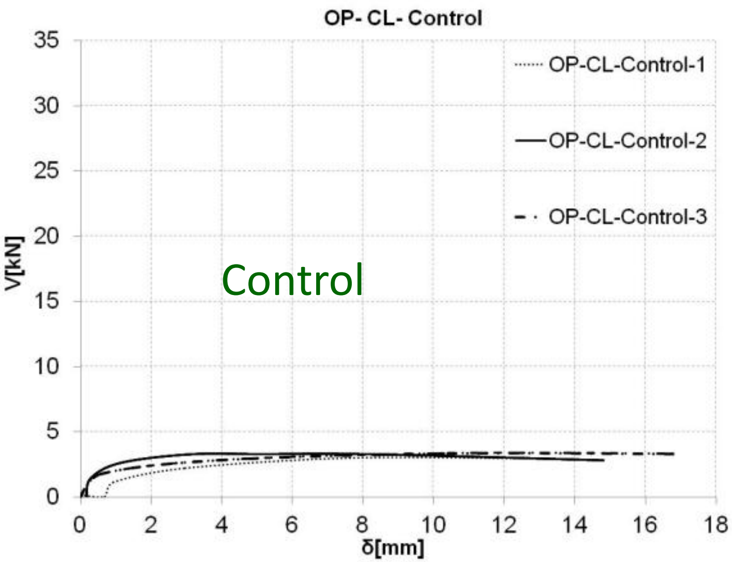
Experimental Results (Out-of-Plane load tests)

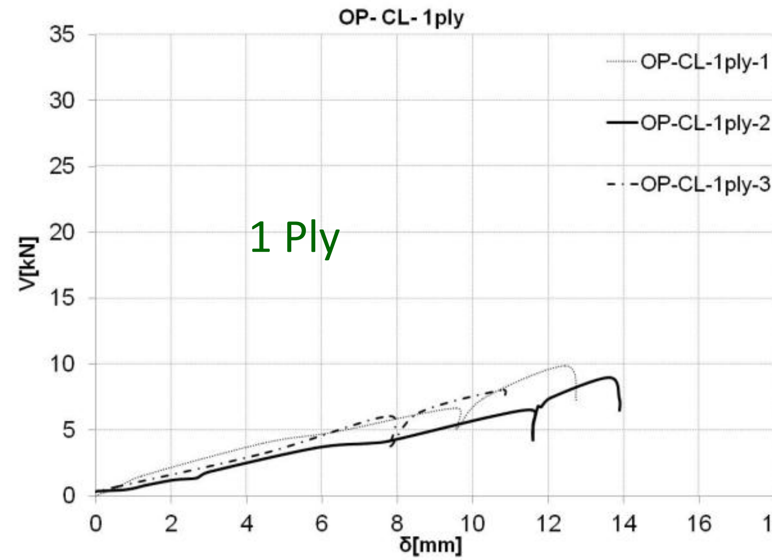
Specimen ID	Exp. Moment M_u Lb.ft	Exp. Strength Enhancement $M_{u,strengthed} / M_{u,control}$	Theoretical Moment(Th.) $M_{u\ Th.}$ Lb.ft	Th. Strength Enhancement $M_{u,strengthed} / M_{u,control}$	Exp / Theo Ratio $M_{u,Exp} / M_{u,Th}$
OP-CMU-Control-X	1745.9	1	553.4	1	3.15
OP-CMU-1 ply-X	4777.1	2.7	1070.1	1.9	4.46
OP-CMU-4 ply-X	13640.6	7.8	4184.9	7.6	3.26
OP-CL-Control-X	1713.9	1	553.4	1	3.10
OP-CL-1 ply-X	4715.4	2.8	1071.8	1.9	4.40
OP-CL-4 ply-X	12874.8	7.5	4211.1	7.6	3.06

1

X is the average of 3 repetitions

Experimental Results (Out-of-Plane load tests of clay walls)





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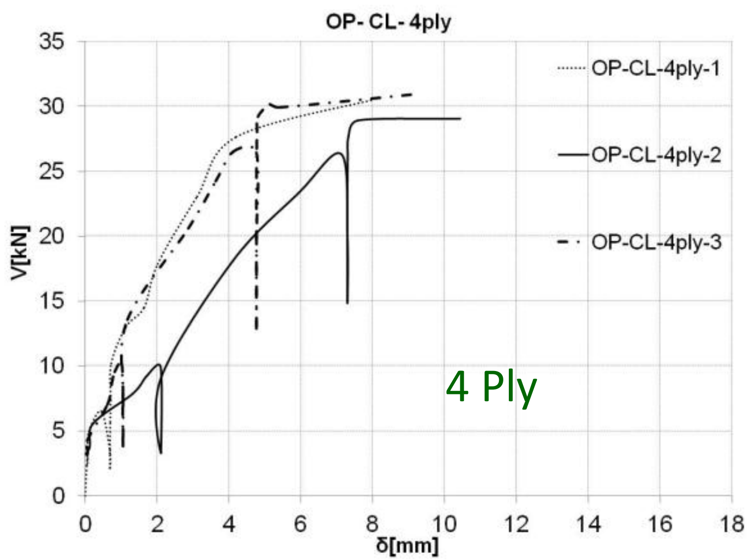


Test matrix (In-Plane loading tests)

Specimen Code	Strengthening Material	Masonry Type	Repetition
I-CMU-Control	None	Concrete Block	3
I-CMU-1Ply	1 Ply of FRCM	Concrete Block	3
I-CMU-4Ply	4 Ply of FRCM	Concrete Block	3
I-CL-Control	None	Clay Brick	3
I-CL-1Ply	1 Ply of FRCM	Clay Brick	3
I-CL-4Ply	4 Ply of FRCM	Clay Brick	3

1

Cont. – Characterization – Test Set up (In-Plane Loading Test)

CMU wall with 1 ply FRCM

Clay brick-control wall

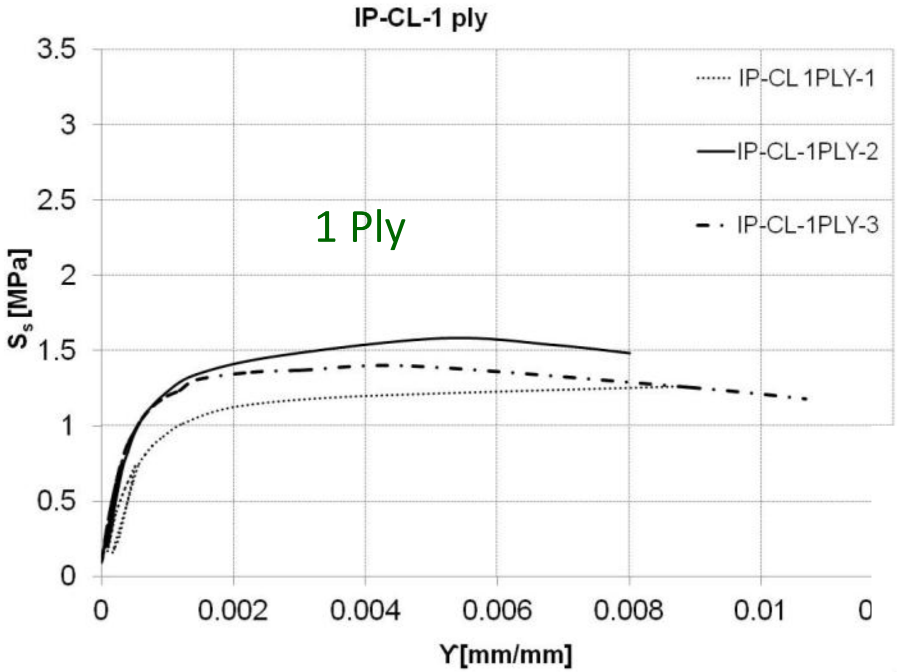
Experimental Results (In-Plane loading tests)

Specimen ID	Exp. P_u kip	Exp. Strength Enhancement $P_u / P_{u,Control}$	Design $P_{u,Th}$ kip	Th. Strength Enhancement $P_u / P_{u,Control}$	Exp/Th. Ratio $P_{u,Exp}/P_{u,Th}$
IP-CL-Control-X	15.7	1.00	10.2	1.00	1.54
IP-CL-1 ply -X	38.2	2.43	14.5	1.37	2.63
IP-CL-4 ply -X	74.1	4.73	15.9	1.50	4.66
IP-CMU-Control-X	24.6	1.00	9.4	1.00	2.61
IP-CMU-1ply-X	47.9	1.95	13.4	1.42	3.58
IP-CMU-4ply-X	57.9	2.36	14.2	1.50	4.10

X is the average of 3 repetitions

1

Experimental Results (In-Plane load tests on clay walls)



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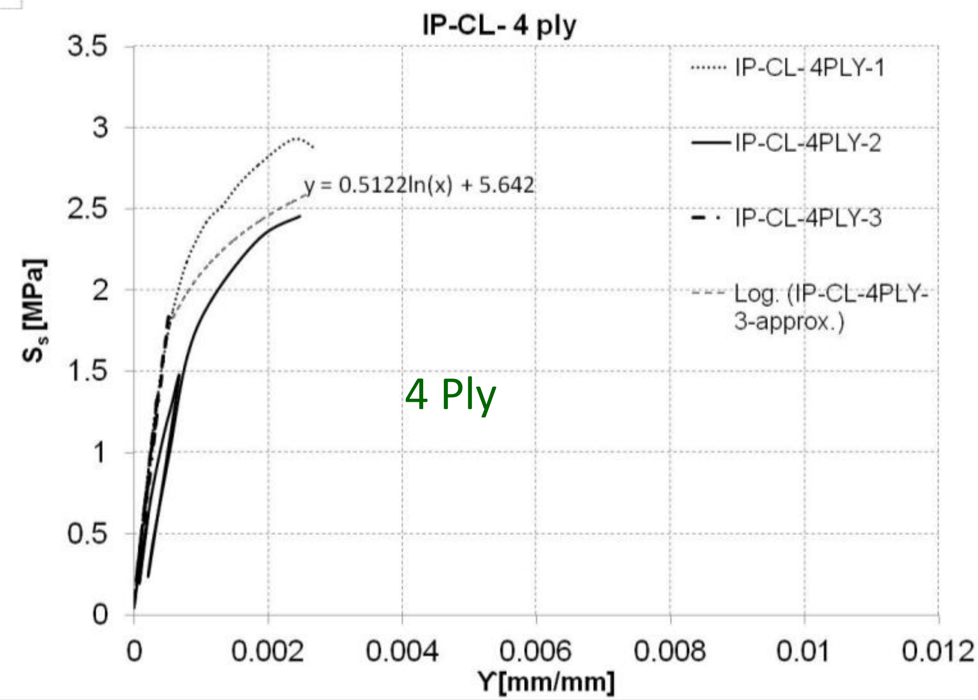


2 FRCM APPLICATIONS – Field projects around the world

Application comprised strengthening a bridge along the Roma-Formia railway in Italy. The 10.5-m wide bridge deck supported by six semicircular plain concrete vaults on masonry abutments made of blocks of tuff

Thickness of each vault varies from 0.7 m at the crown to 1.0 m at the skewback

2

Bridge structure with scaffolding

STRENGTHENING UNREINFORCED CONCRETE VAULTS (cont.)

Worker installs FRCM onto soffit of concrete vault. Worker advances rolls of the fiber network

2

Second fabric installed over the first layer. Rolls of the fiber network hang from the vault as the scaffolding is advanced

STRENGTHENING A REINFORCED CONCRETE BRIDGE PIER

Strengthening of a reinforced concrete bridge pier in Novosibirsk, Russia. Significant cracking had appeared since pier reconstructed in 1958 . In 1991, cracks were epoxy-injected, but inspections in 1997 indicated that cracks had reopened, with widths ranging from 2 to 5 mm

2

Reinforced concrete bridge pier. Numerous cracks repaired using epoxy injection

STRENGTHENING A REINFORCED CONCRETE BRIDGE PIER (cont.)

Workers repoint cracks prior to application of FRCM strengthening

3

Workers trowel top finish over FRCM network within a heated tent

REPAIR OF TRESTLE PEDESTALS

FRCM used to provide confinement and protection to concrete pedestals supporting Metro North Railway trestle in northern New York State. Pedestals have truncated pyramid shape and vary in size depending on configuration of ground

Structural steel trestle supported by numerous trapezoidal concrete pedestals

2

Worker prepares pedestal (measuring about 2.4 by 2.4 m at base and 2.4 m in height) by removing deteriorated concrete

REPAIR OF TRESTLE PEDESTALS (cont.)

Worker patches the substrate

Workers apply a fiber network over layer of cementitious mortar

2

STRENGTHENING OF A REINFORCED CONCRETE TUNNEL LINING

FRCM used for strengthening of a concrete lining for vehicular tunnel (Egnatia Odos Motorway, Greece). FRCM used to overcome deficiency of internal steel reinforcement in 650-mm thick lining. Lining originally reinforced with two steel bar mats, each with 50 mm cover

Surface preparation by hydrojetting

Application of FRCM at top portion of tunnel lining

STRENGTHENING A MASONRY CHIMNEY

3

Strengthening of unreinforced masonry chimney of historic sawmill in Gerardmer, France. Chimney preserved as symbol of region's industrial heritage and used to support telephone antennas and their cabling.
Height of about 38 m, with diameter ranging from 3.60 to 1.70 m from base to summit

Chimney surrounded by scaffolding during FRCM repair

STRENGTHENING A MASONRY CHIMNEY (cont.)

2

Original masonry surface before repair. Clay bricks and sand-lime joints with high capillary absorption. Cementitious matrix to repair the existing surface without any pretreatment

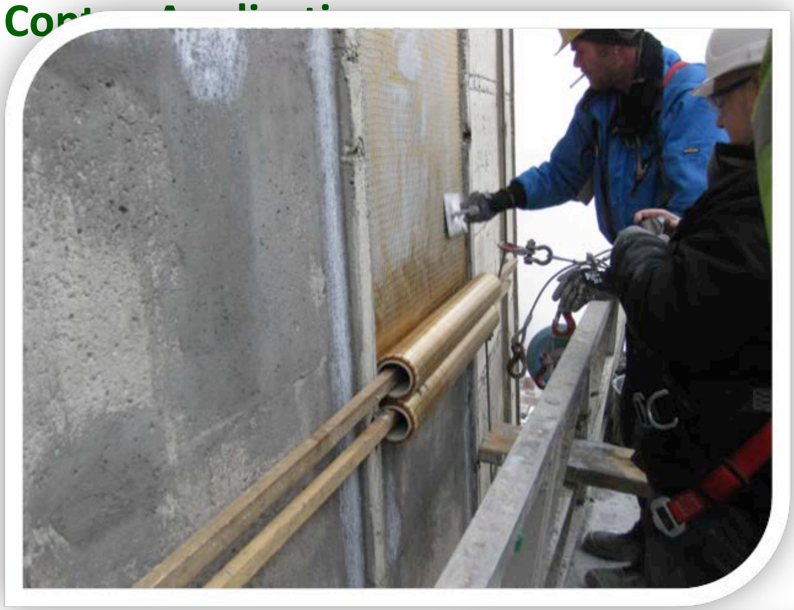
Fiber network pressed into cementitious mortar applied directly to substrate

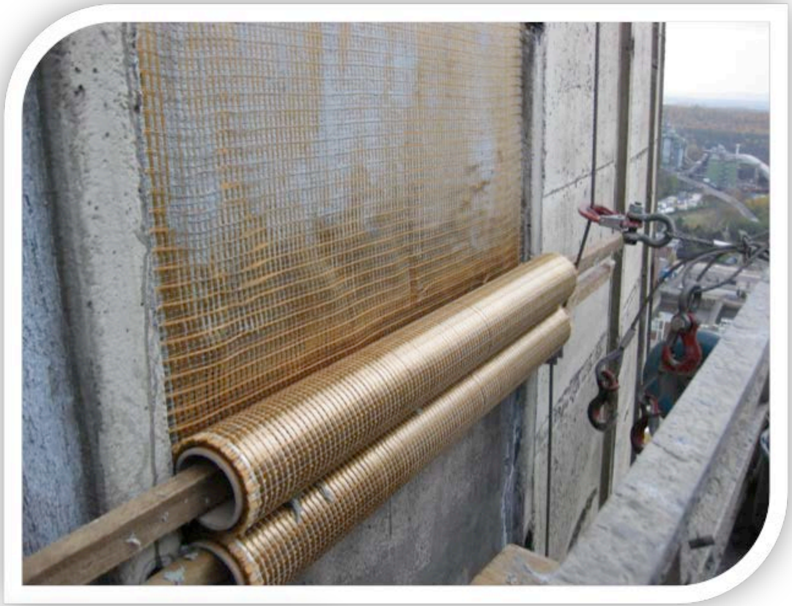
2

Thermal Power Plant (Germany)

Cont. – Applications

2





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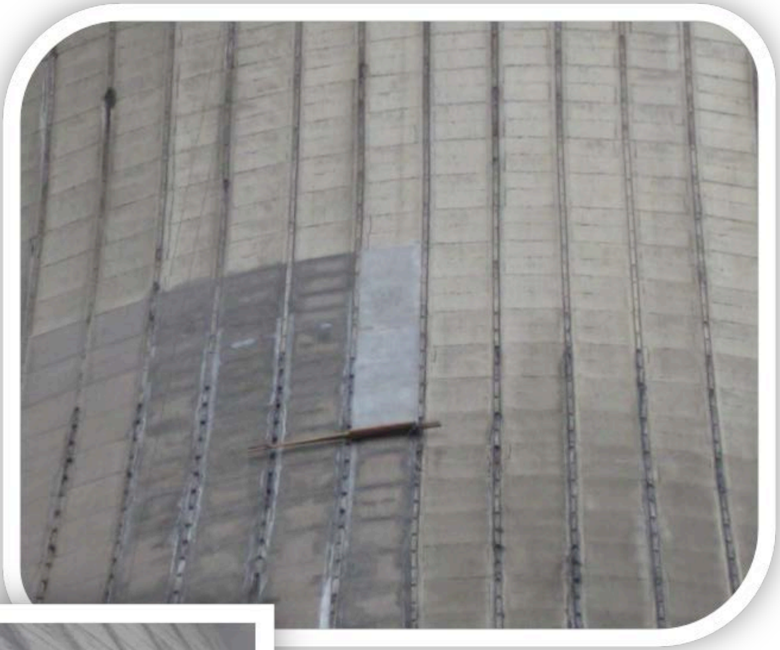

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3 TOOLS FOR DESIGNERS AND CONTRACTORS – AC434 and ACI 549 proposed guide

- **Criteria for evaluation and characterization of FRCM systems used to strengthen existing masonry and concrete structures** developed by ICC-Evaluation Service (ICC-ES) as AC434
- Modifications to the October 2011 version approved at the ICC-ES public hearing of 02/13/2013

ICC EVALUATION SERVICE

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PROPOSED REVISIONS TO THE ACCEPTANCE CRITERIA FOR MASONRY AND CONCRETE STRENGTHENING USING ~~FIBER~~ FABRIC-REINFORCED CEMENTITIOUS MATRIX (FRCM) COMPOSITE SYSTEMS

AC434

Proposed December 2012

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- For FRCM manufacturers, AC434 establishes the guidelines for tests and calculations in order to receive a product **Research Report** from ICC-ES

Cont. – Introduction – How innovation is handled by ACI: ACI 549

- A new document **ACI 549.xR-xx** was approved by ACI 549 Committee and now at TAC for review
- ACI 549 is harmonized with the revised version of AC434 and uses its protocols for FRCM characterization

ACI 549.xR-xx; December 28, 2012

DESIGN AND CONSTRUCTION GUIDE OF EXTERNALLY BONDED FRCM SYSTEMS FOR CONCRETE AND MASONRY REPAIR AND STRENGTHENING

Reported by ACI Committee 549

Jones, John (Chair)

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Gilbert, Graham	Zellers, Robert C
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*Members of the subcommittee that prepared this document.
The Committee also thanks Associate Member J. Gustavo Tumialan for his contribution.

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CONCLUSIONS

- Coupon tests allowed for the proper characterization of FRCM properties required for the certification of the material systems
- The structural element tests (i.e., RC slabs, beams and columns, and masonry walls) allowed for the establishment of structural benchmark performance using extremes of FRCM use (i.e., 1 and 4 plies)
- The reapproved AC434 is in harmony with the ACI 549 guide under TAC approval at ACI. The outcome of this process will provide the practicing community with the needed tools for material selection, design and installation.
- After a decade of incubation time, FRCM is now being considered as another tool in the repair toolbox combining some of the advantages of both FRP and the cementitious matrix. Some challenges in its characterization and full-exploitation remain
- Repair of concrete structures represents an untapped opportunity worldwide for the use of new materials applied as "skin" to existing substrates (concrete and masonry)