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Structural Repair and Retrofit using Fabric Reinforced Cementitious Matrix (FRCM)

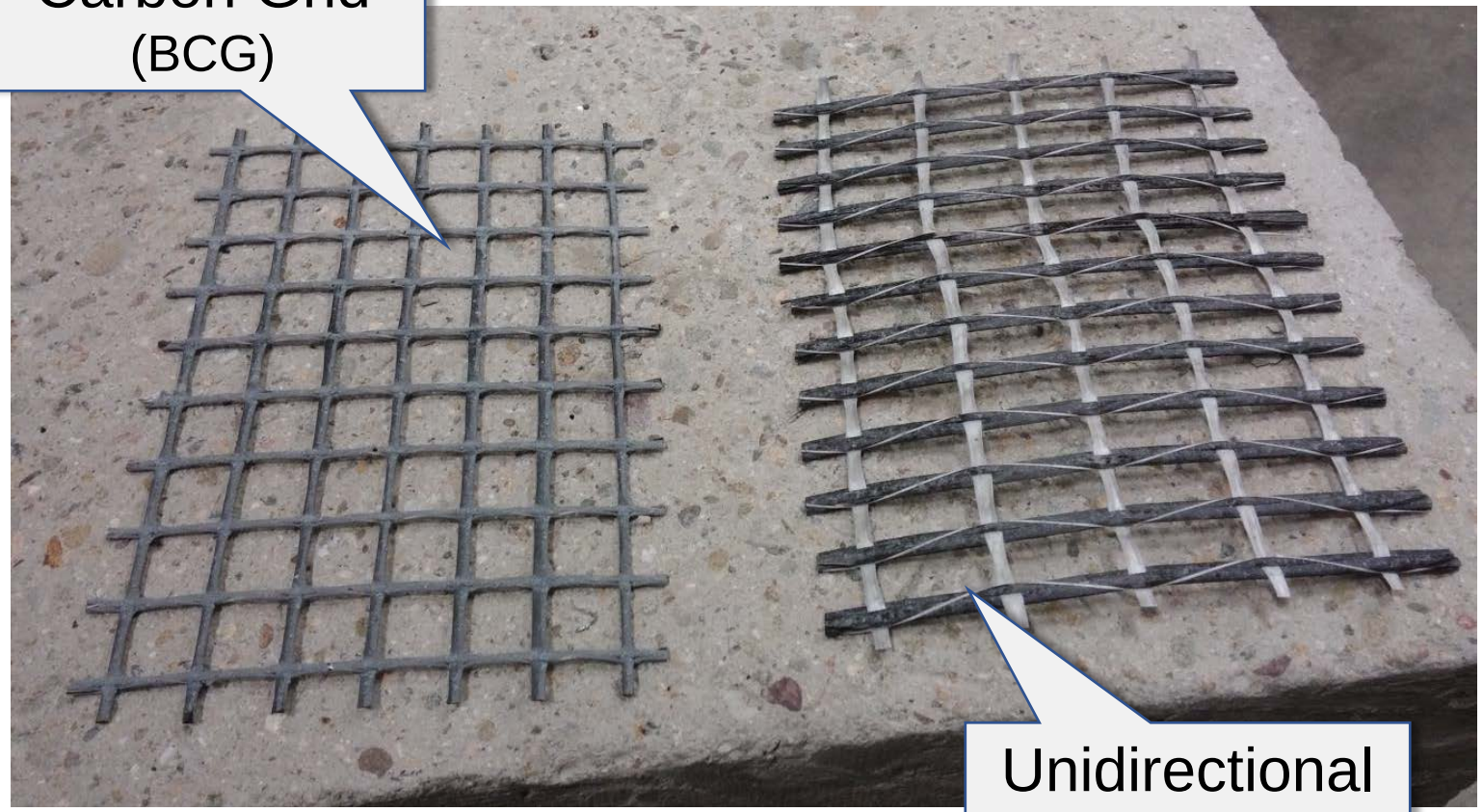
Aniket Borwankar
Senior Development Manager
Composite Strengthening Systems
Simpson Strong-Tie

What is FRCM?

Fabric-Reinforced Cementitious Matrix (FRCM) System = Carbon-Fiber Grid + Cementitious Matrix

FRCM Grid types and properties

Bidirectional Carbon Grid (BCG)



Unidirectional Carbon Grid (UCG)

MATERIAL PROPERTIES

Grid Properties

Weight	13 oz./yd.^{2} (440 g/m^2)
Weight of fibers	8.3 oz./yd.^{2} (280 g/m^2)
Equivalent Dry Fabric Thickness (in strong direction)	0.0062 in. (0.157 mm)
Ultimate Tensile Strength	31 kip/ft. (450 kN/m)
Ultimate Tensile Strain	1.5%
Axial Stiffness by width unit	2,067 kip/ft. (30,000 kN/m)
Area by width unit	0.0064 in.^{2}/in. (162 mm^2/m)
Color	Gray

Cured Composite Properties[1]

Property	Design Value[2]
Cracked Tensile Modulus	7.1 x 10^6 psi (49,000 MPa)
Ultimate Tensile Strain	1.1%
Ultimate Tensile Strength	128,300 psi (885 MPa)
Lap Tensile Strength	121,000 psi, 12" lap (834 MPa, 30 cm)
Thickness per Layer	0.55 in. (14 mm)

1. When installed with CSS-CM cementitious matrix.
2. Average tensile strength and strain minus one standard deviation per ACI 549. Modulus values are average.

Traditional Shotcrete vs. FRCM

Traditional Shotcrete Repair

FRCM Repair

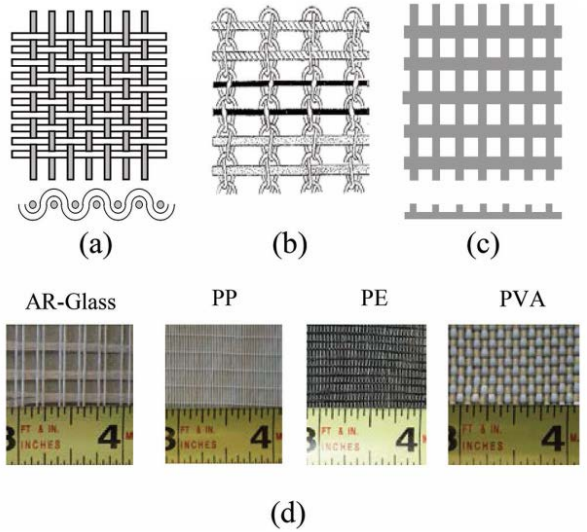
Traditional Shotcrete vs. FRCM

Traditional Shotcrete Repair	FRCM Repair
❑ Specialty contractor to tie rebar cage ❑ Specialty contractor to spray shotcrete	✓ Same contractor installs FRCM system
❑ Rebar installation time-intensive	✓ Carbon-fiber grid installs in minutes, saving time and money
❑ Additional 1.5″–3″ shotcrete cover over rebar	✓ No steel = no cover requirements. Only ≈1″ volume change in total repair
❑ Additional weight needs to be calculated into total building loads	✓ Adds negligible weight to structure
❑ Shotcrete typical psi at 4,000 psi	✓ Cementitious matrix is a high-performance mortar with psi at 7,500 psi

ACI 549.4R-20 & ACI 549.6R-20 is the current design guide

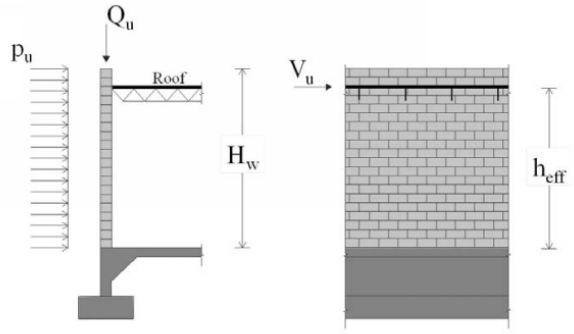
- Background
- Research
- Installation
- Evaluation
- Field Testing
- Applications
- Design examples

(From ACI 549.4R-13)



16.6-Flexural strengthening of unreinforced masonry wall (URM) subjected to out-of-plane loads

A warehouse roof is built with steel open-joists and beams supported by steel interior columns and load bearing unreinforced ungrouted CMU walls along the building perimeter. A change in use ot he warehouse has warranted the increase of the design lateral wind load. The existing CMU is not adequate to resist the new loads. Summarized in the following sections are the information about the typical existing wall panel and the existing and new loading conditions. The schematic of the wall panel under out-of-plane condition is shown in the figure below. The wall is assumed fixed at the base and simply supported at the roof level. The existing masonry wall panel is strengthened with FRCM, whose mechanical properties are reported in the following.



Wall panel schematic

ICC-ES AC434 is used for evaluating FRCM products

- Physical/mechanical properties
- Durability (water, SW, alkali)
- How to grip material?
- Component testing
- Full scale testing*

TABLE 3—ENVIRONMENTAL DURABILITY TESTS

ENVIRONMENTAL DURABILITY TEST	RELEVANT SPECIFICATION	TEST CONDITION	TEST DURATION	PERCENT RETENTION	
				Hours	
				1,000	3,000
Water resistance	ASTM D2247 ASTM E104	100%, 100 ± 2°F	1,000 and 3,000 hours	85	80
Saltwater resistance	ASTM D1141 ASTM C581	Immersion at 73 ± 2°F			
Alkali resistance	ASTM C581	Immersion in solution with pH = 9.5 or higher and 73 ± 3°F			
Salt spray*	ASTM D1141 ASTM G85	73 ± 2°F			

* For SRG fabric only.

In the primary direction (0°), the carbon grid composites have a minimum design ultimate tensile strength of 128.3 ksi (885 MPa), a minimum design cracked tensile modulus of 7,100 ksi (49,000 MPa) and a corresponding design elongation of 1.1 percent. The fabric area by unit width is 0.0062 inch^2/inch (157 mm^2/m).

Basic

Component

Full scale

Current FRCM Testing

ESR Report: ICC-ES ESR-3506

Abrasion

- ASTM C779, “Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces”

Aging: Water Resistance ASTM D2247:

- “No specimens showed surface changes such as erosion, cracking, crazing and chalking after a visual inspection, meeting the conditions of acceptance of AC434, as well as a minimum average of 85 or 80 percent retention for the 1000 & **3000 hrs. exposure,** respectively for tensile strength, interlaminar shear strength, lap tensile strength and tensile bond strength”

Permeability: ASTM C1202:

- Mortar was tested per ASTM C1202 - Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration

MATERIAL PROPERTIES

Matrix Properties

Unit Weight	140 lb./ft.³ (2,240 kg/m³)
Set Times (ASTM C191)	**Initial Set:** <5 hr. **Final Set:** <8 hr.

Matrix Test Properties[1]

Property	Design Value
Tensile Modulus (ASTM C469)	3,880,000 psi (26.8 GPa) @ 28 days
Rapid Chloride Permeability (ASTM C1202)	<500 coulombs (very low) @ 28 days
Freeze/Thaw Resistance (ASTM C666, Proc. A)	93.7% RDM @ 300 cycles
Salt Scaling Resistance (ASTM C672)	0.06 lb./ft.² (very slight) @ 50 cycles
Sulfate Resistance (ASTM C1012)	+0.02% @ 6 mo.
Direct Tensile Bond Strength (ASTM C1583)	28 day: 390 psi (2.7 MPa)
Direct Shear Bond Strength (Michigan DOT)	28 day: 300 psi (2.1 MPa)
Slant Shear Bond Strength (ASTM C882, mod.)	28 day: 2,630 psi (18.1 MPa)
Splitting Tensile Strength (ASTM C496)	28 day: 700 psi (4.8 MPa)
Flexural Strength (ASTM C348)	28 day: 1,000 psi (6.9 MPa)
Compressive Strength (ASTM C109)	1 day: 3,000 psi (21 MPa) 7 day: 6,300 psi (43 MPa) 28 day: 7,500 psi (52 MPa)
Drying Shrinkage (ASTM C157, mod.[2])	-0.09% @ 28 days

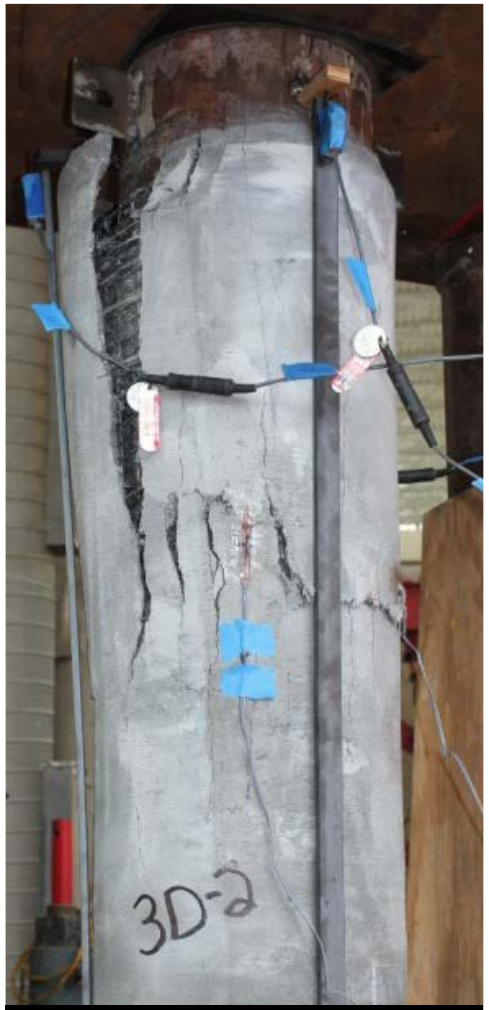
FRCM Testing

- Axial Column
- Beam Flexure
- Beam Shear
- Out-of-plane Wall
- In-plane Wall
- Slab
- Tensile Testing for Composite Design Values
- Exterior Exposure
- Durability
- Interlaminar Shear
- Drying Shrinkage
- Void Content
- Freeze/Thaw
- Lap Tensile Strength
- Full Scale Fire
- Bond Strength
- Abrasion Resistance
- Permeability

FRCM Structural Testing: Column Testing Results

Control
285,000 lb

1 Layer UCG
485,000 lb



2 Layer UCG
650,000 lb

Some benefits and limits of using FRCM

+

- Heat resistance
- Breathable
- Durable
- Repairs
- Strengthens
- Stiffens
- Uneven surfaces
- Adds cover (rebar)
  - Corrosion
  - Fire

From ACI 549.4R

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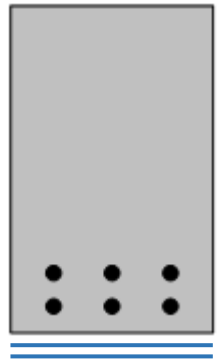
- Gravity check
- Size
- Limited strength

Gravity strength increase requires a special check

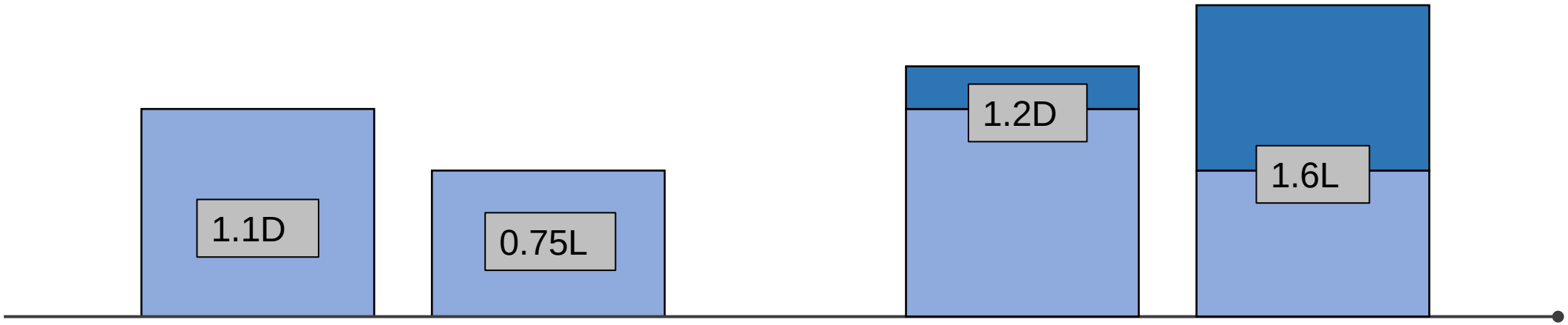
Capacity of FRCM strengthening

Capacity of existing reinforced concrete section



Existing reinforced concrete section

Added FRCM



$$(\varphi R_n)_{existing} \geq (1.1S_{DL} + 0.75S_{LL})_{new}$$

$$(\varphi R_n)_{strengthened} \geq (1.2S_{DL} + 1.6S_{LL})_{new}$$

And technically another check…fire

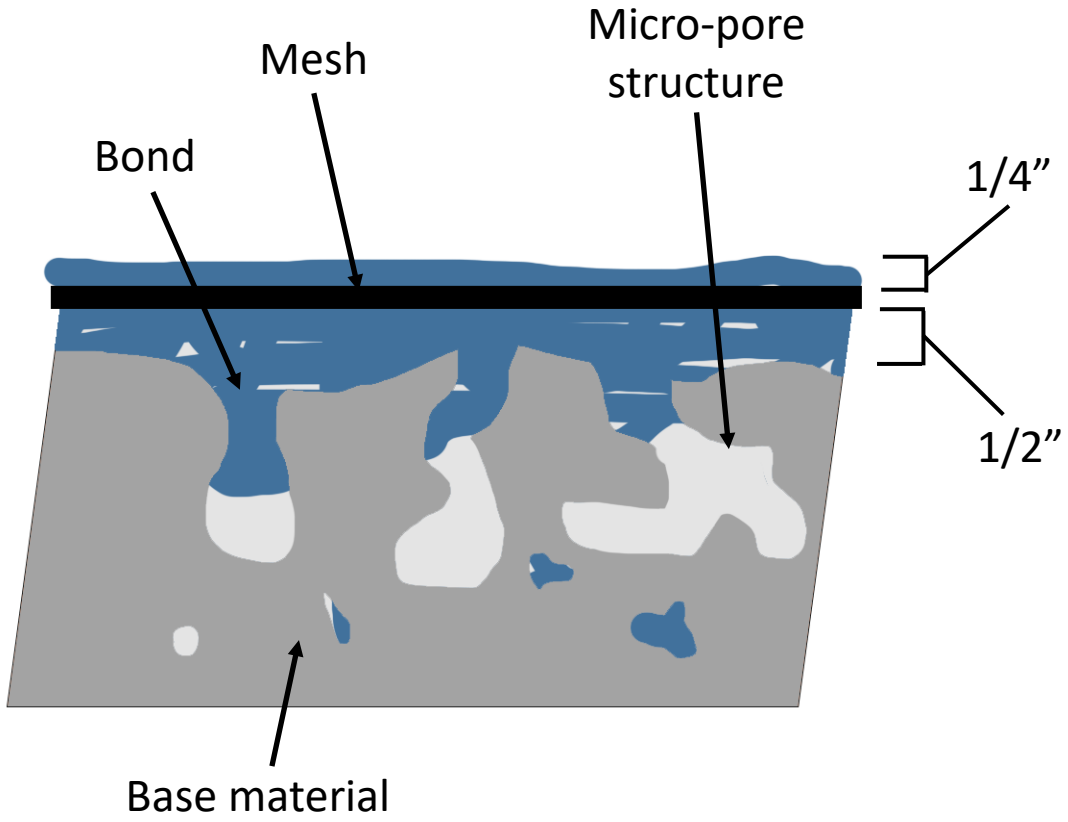
$$1.2D + 0.50L + 0.20S \leq \phi_{ex} R$$

ϕ_{ex}: 1.0

R: Nominal strength considering temperature

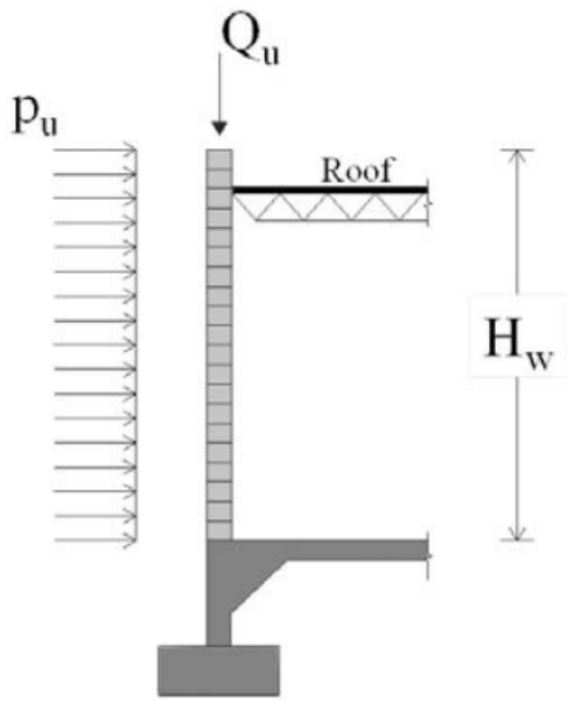
Surface preparation helps ensure a good bond

- Grinding, hydro-jetting, etc.
- Remove paint
- SSD
- Wet burlap
- 200 psi min. bond desirable*

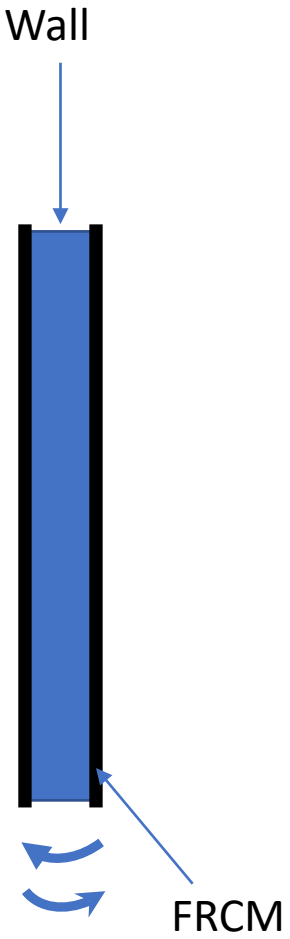


FRCM can be used for different applications

- Flexural
  - Beams
  - Walls (Out-of-plane)
  - Slabs
- Shear
  - Beams
  - Walls (In-plane)
- Axial
  - Columns
  - Piers



Out-of-plane condition

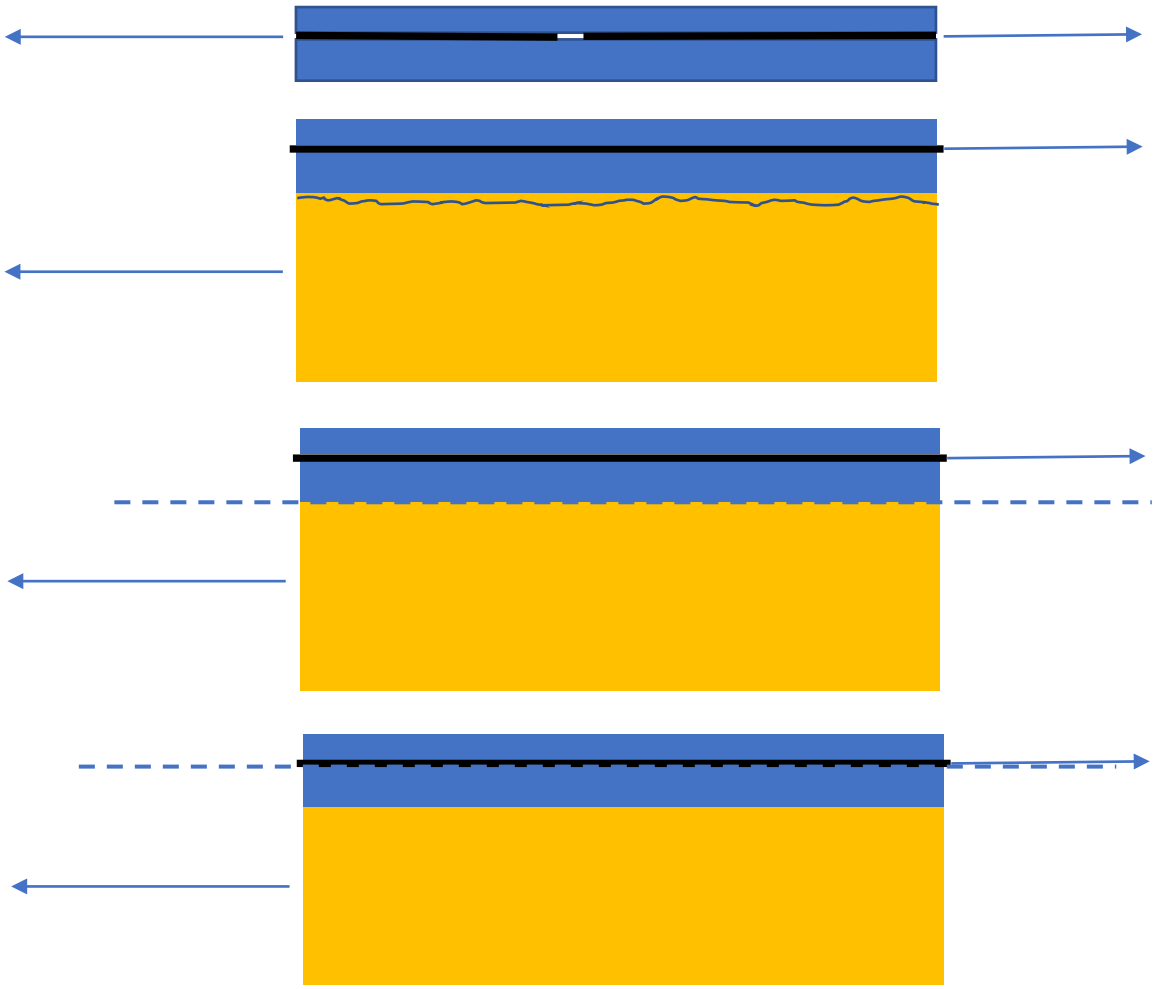


FRCM can be used on different base materials

- Concrete
- CMU
- Brick
- Stone

FRCM has 4 basic failure modes

- Mesh
- Cohesive
- Adhesive
  - FRCM/base material interface
  - Mesh/matrix interface



Gruening Middle School suffered damage during a 2018 Alaska Earthquake

Photo: Ellen Hamel, S.E. with Reid Middleton, Inc.

The school has several deficiencies

- Horizontal and vertical reinforcement
- Out-of-plane bending capacity
- Crack control

How was FRCM Detailed by the SEOR?

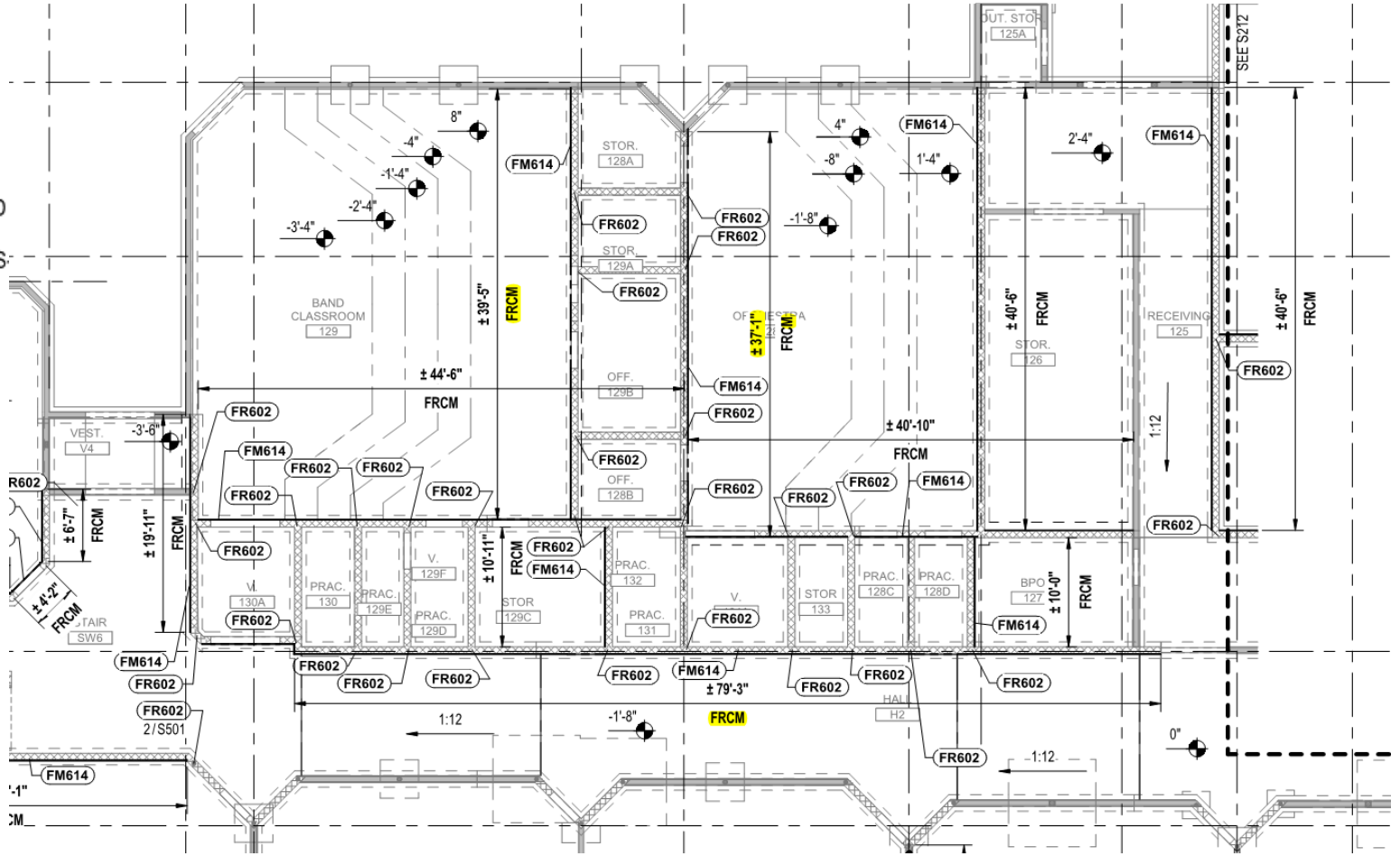
FABRIC-REINFORCED CEMENTITIOUS MATRIX (FRCM/FABRIC MATRIX)
NOT ALL WALLS NEED THE ADDITION OF FABRIC-REINFORCED CEMENTITIOUS MATRIX (FRCM/FABRIC MATRIX). WALLS NOT INCLUDED EITHER HAVE SUFFICIENT EXISTING REINFORCEMENT OR ARE BEING STRENGTHENED THROUGH OTHER MEANS.

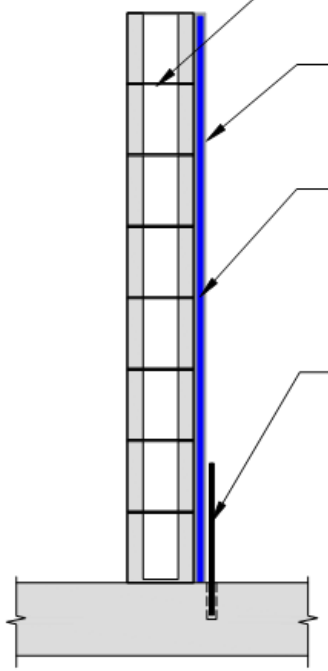
PROPOSED FABRIC MATRIX SYSTEM SHALL HAVE A CURRENT ICC EVALUATION REPORT AND BE INSTALLED ACCORDING TO THE CONTRACT DOCUMENTS, MANUFACTURERS AND ICC RECOMMENDATIONS AND PROCEDURES. DRAWINGS ARE BASED ON THE FOLLOWING BASIS-OF-DESIGN MATERIAL FROM SIMPSON STRONG-TIE:

SINGLE-SIDED APPLICATIONS:
- GRID - CSS-BCG, BI-DIRECTIONAL CARBON GRID
- MATRIX - CSS-CM, CEMENTITIOUS MATRIX
- THICKNESS = +/-1/2" FROM FACE OF EXISTING CMU

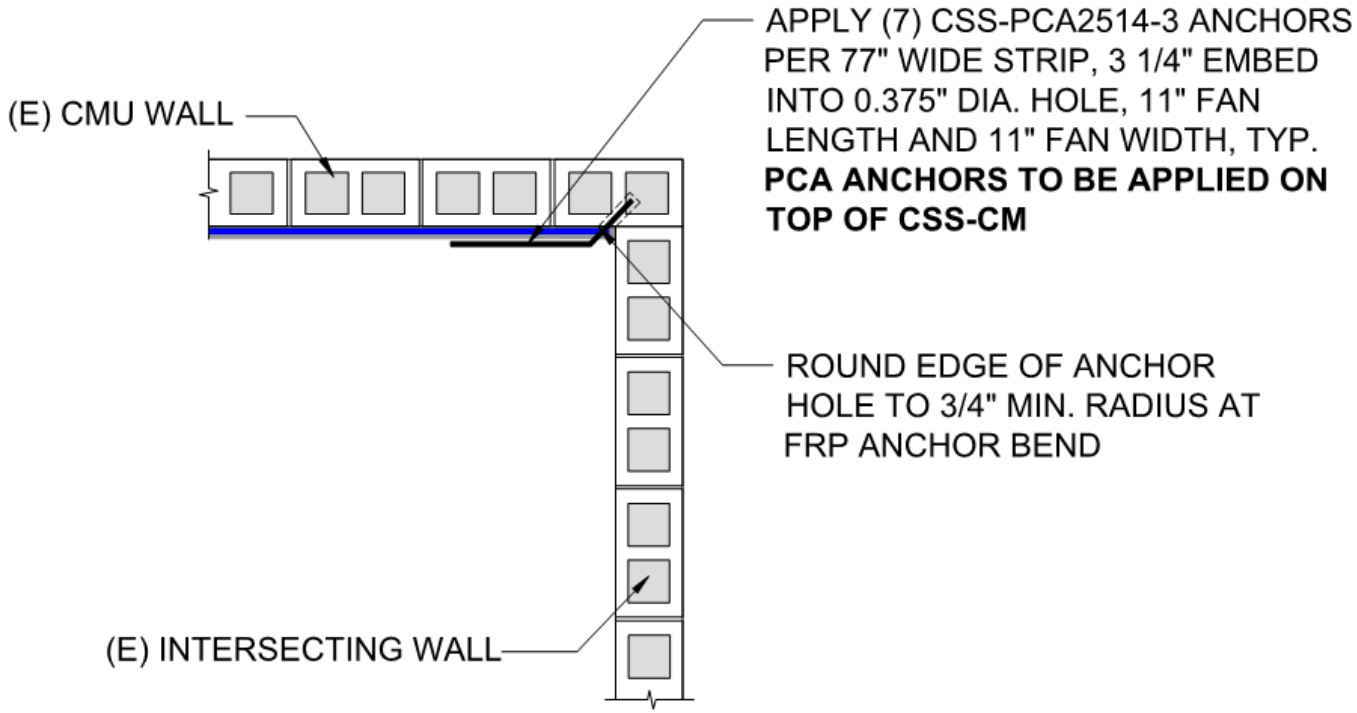
DOUBLE-SIDED APPLICATIONS: (STAGE AREA OF MPR AS NOTED ON DRAWINGS)
- GRID - HBCG, HEAVY BI-DIRECTIONAL CARBON GRID
- MATRIX - CSS-CM, CEMENTITIOUS MATRIX
- THICKNESS = +/-1/2" FROM FACE OF EXISTING CMU
- STRENGTH REQUIREMENTS - FLEXURAL CAPACITY OF 900 LBFT/FT

CMU MITIGATION SHALL BE FRCM/FABRIC MATRIX APPLIED ON THE ENTIRE FACE FROM THE TOP OF SLAB TO THE UNDERSIDE OF THE FLOOR OR ROOF SHEATHING WHERE INDICATED. MATRIX SHALL BE SUFFICIENTLY ANCHORED AT EACH END AND BETWEEN LEVELS.



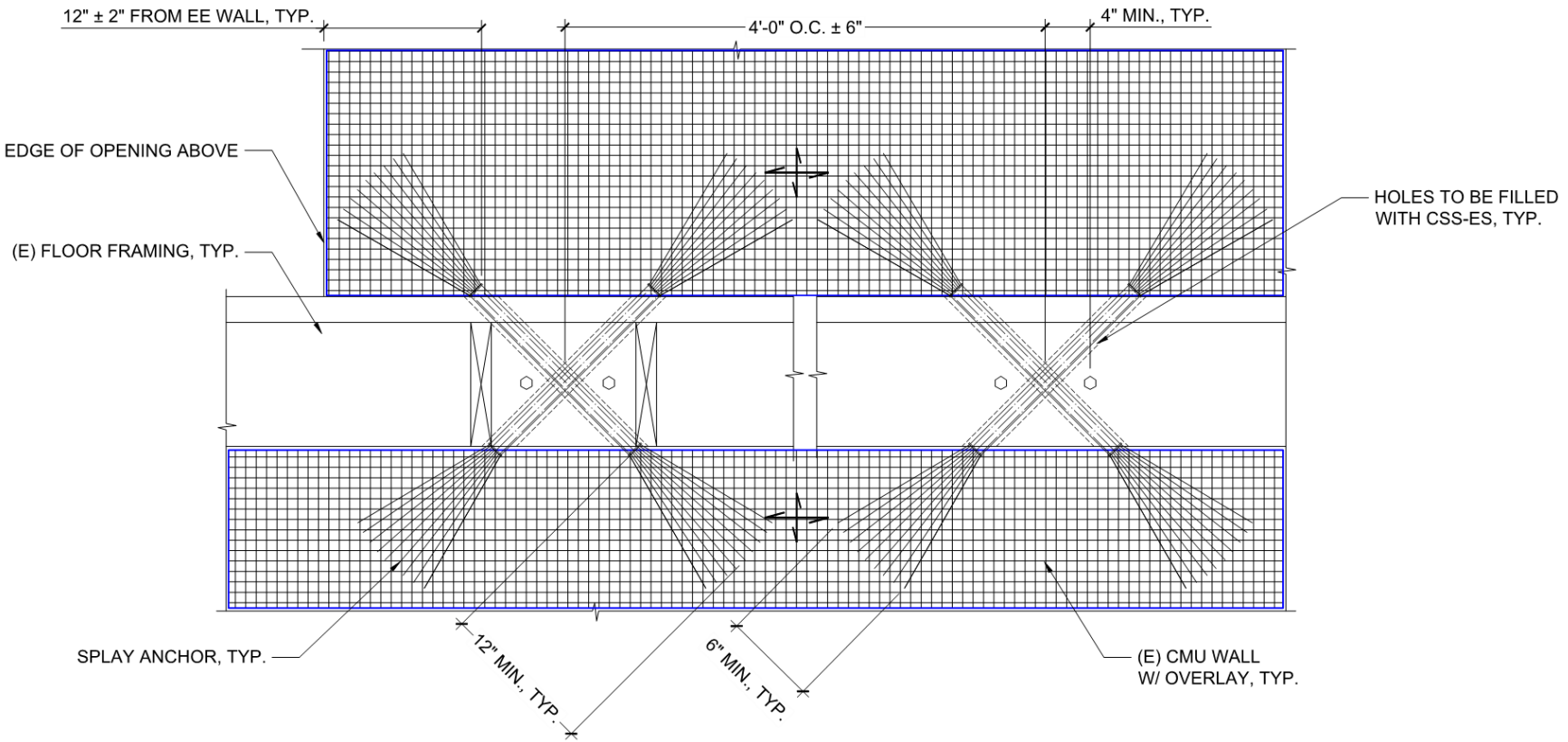


SECTION A



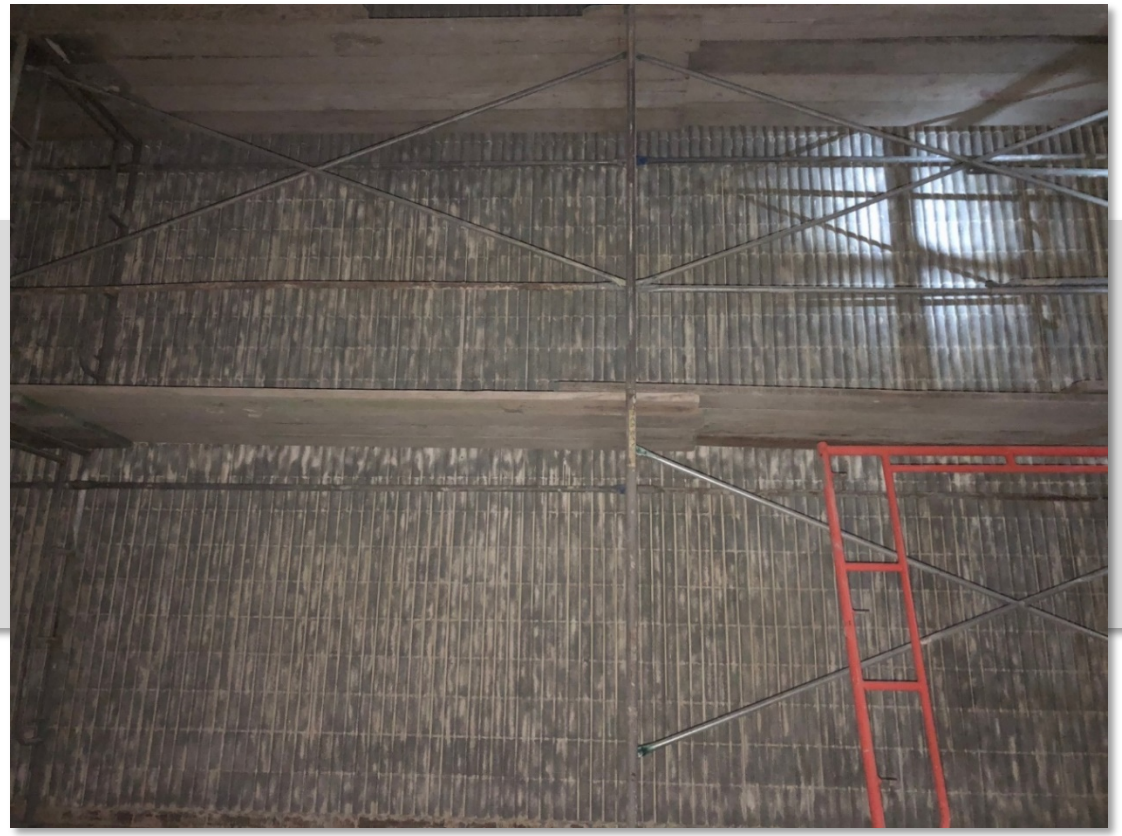
SECTION B

DETAIL FOR WOOD FLOOR FRAMING - FRCM ANCHOR OPTION



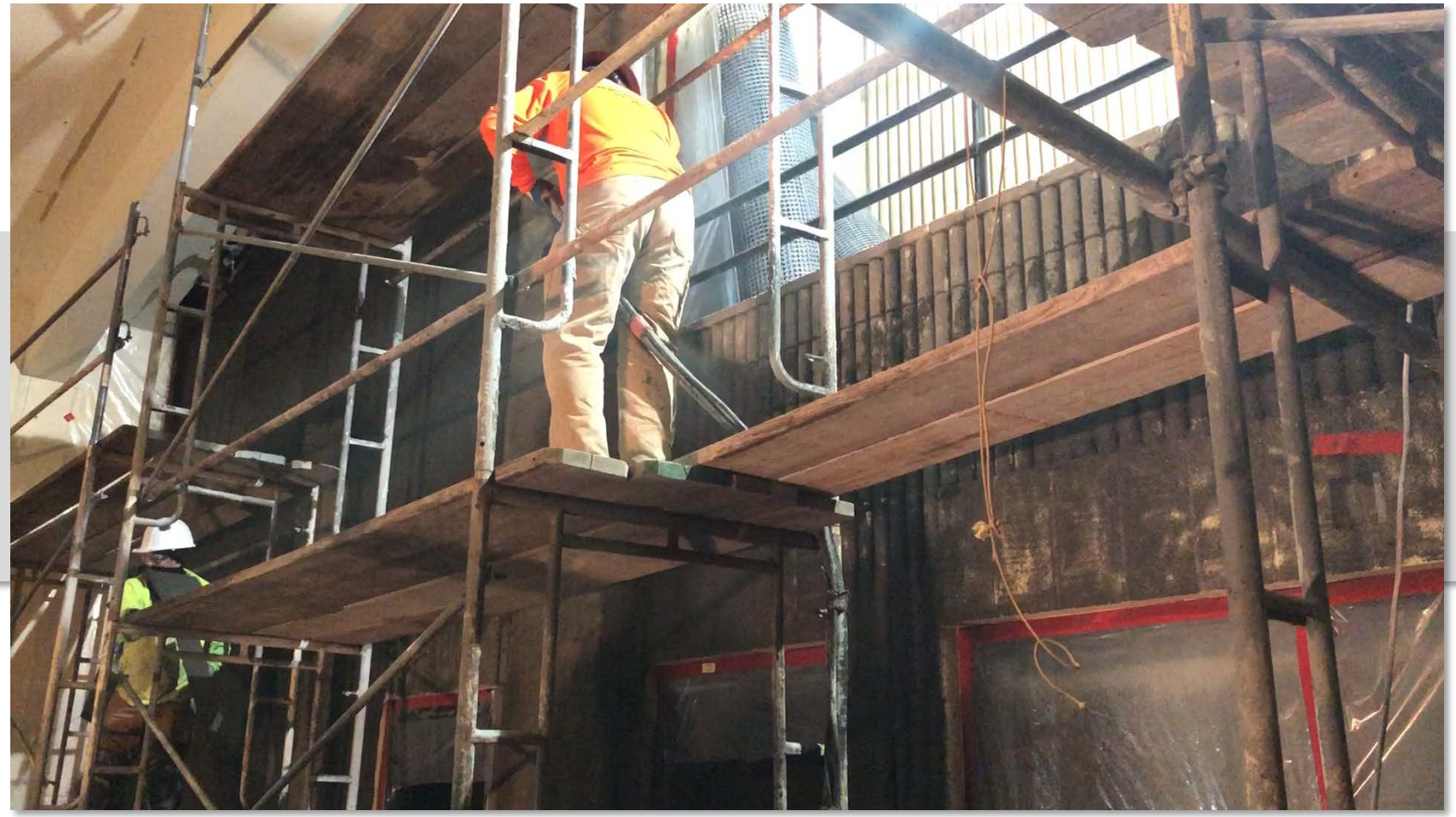
SPLAY ANCHORS IN ELEVATION

Approximately 40,000 ft^2 of masonry walls were strengthened using FRCM

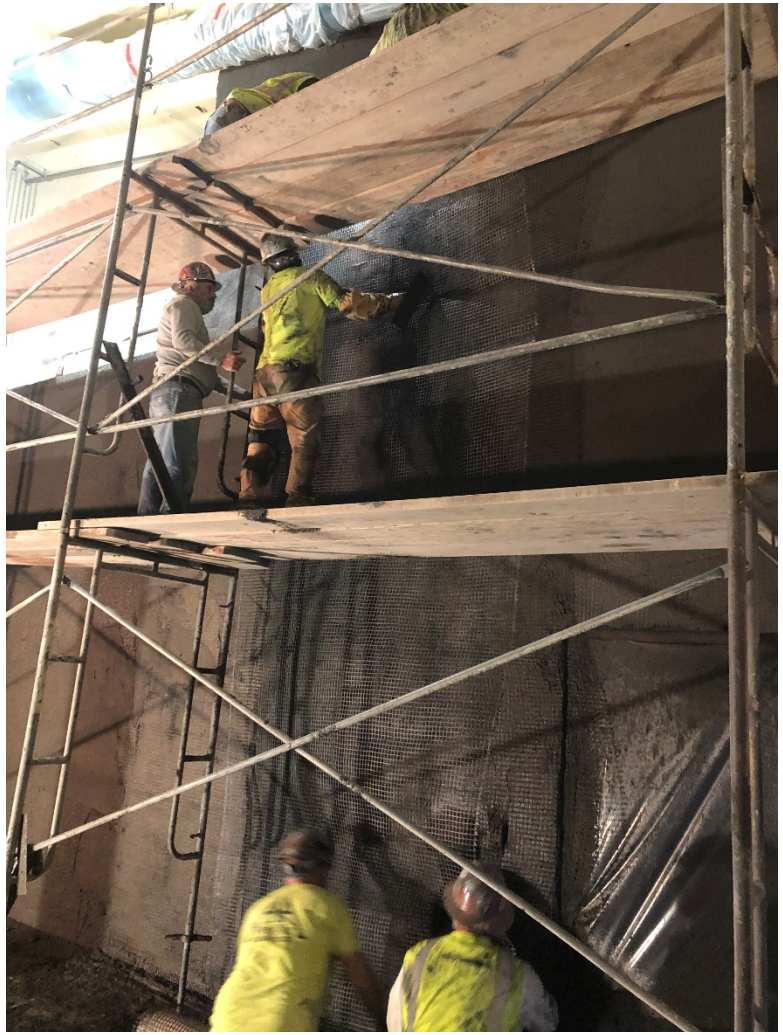


The CM base coat is first applied

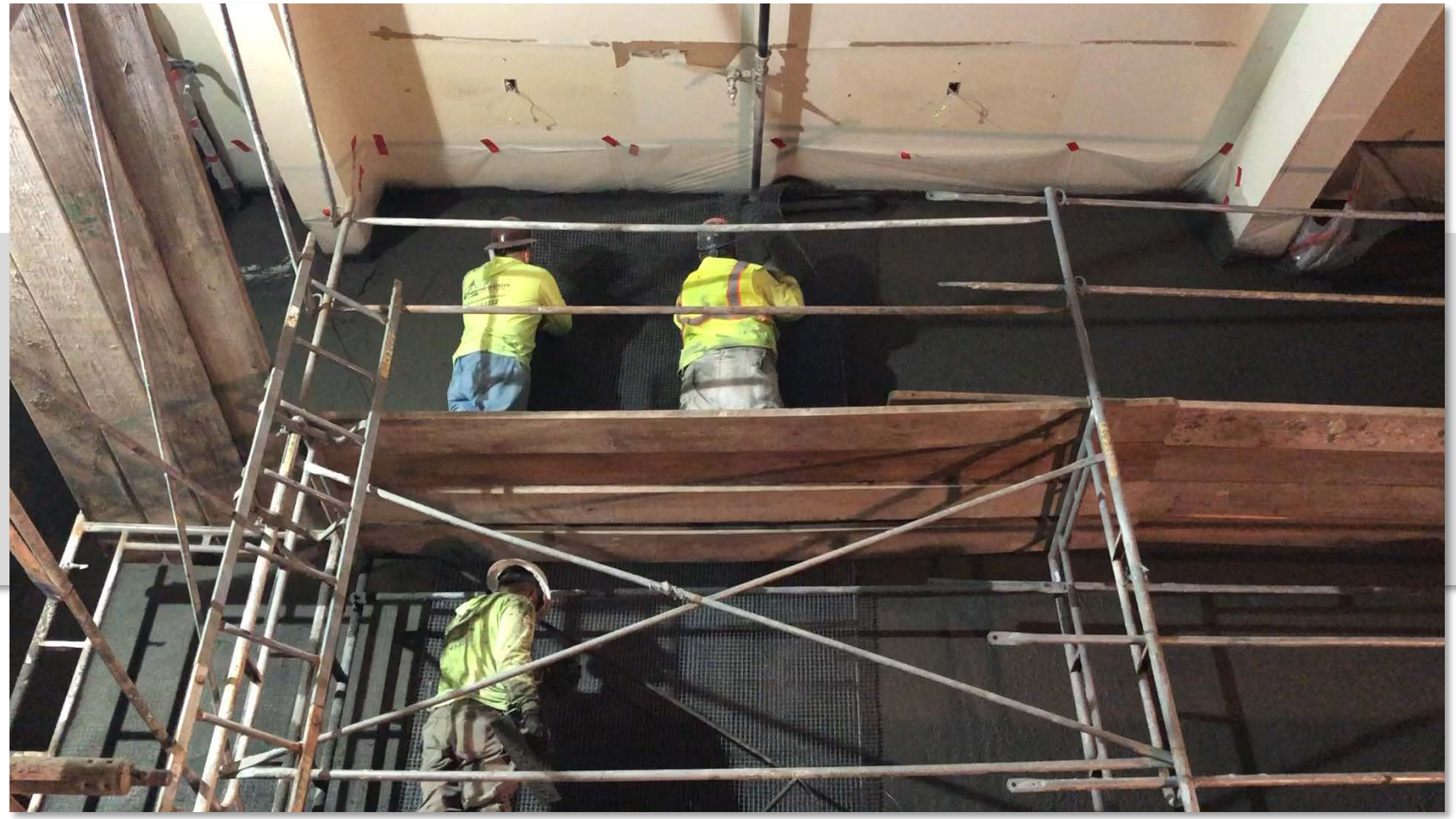
Spray-on CM made filling between CMU flutes easy



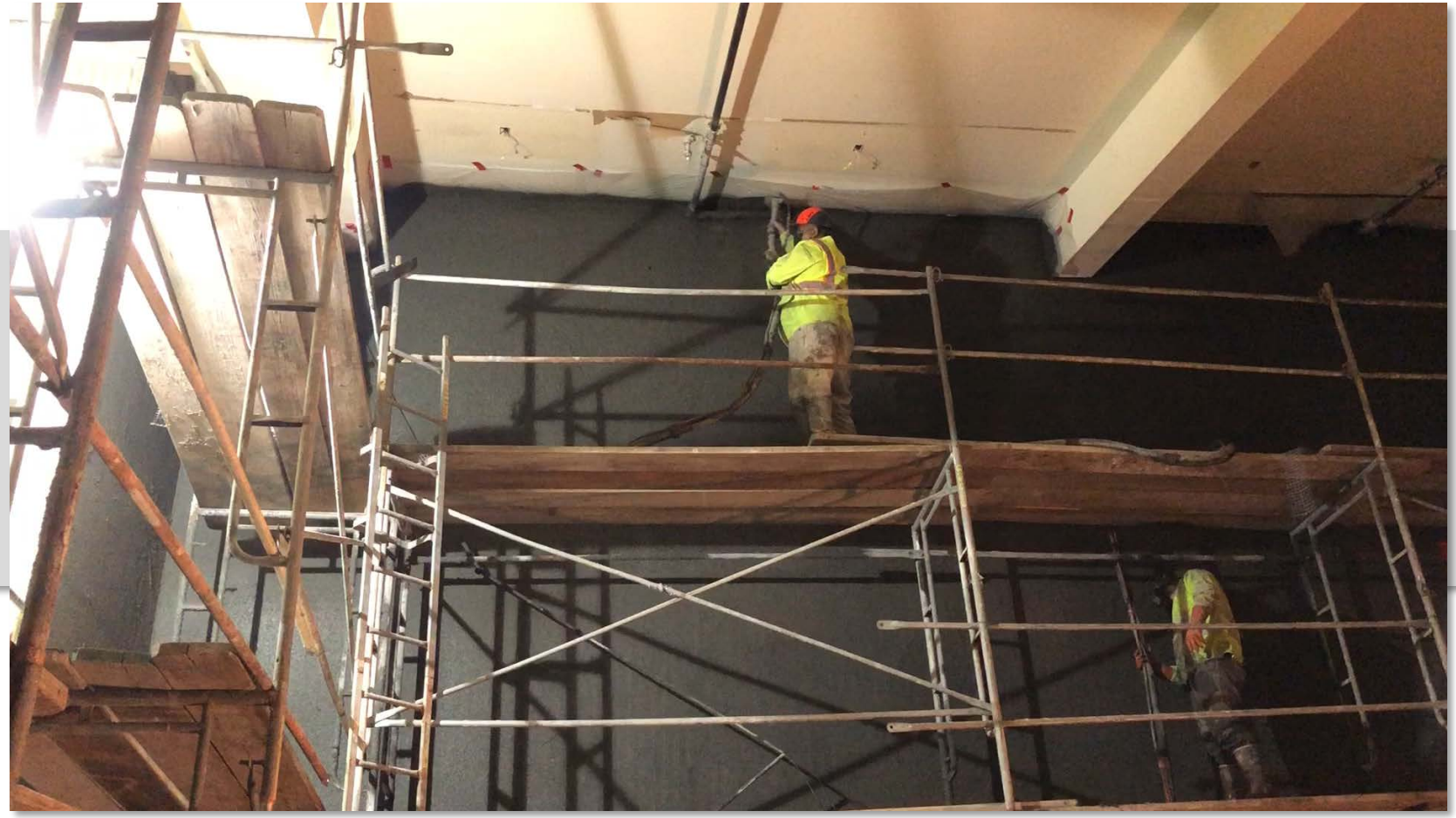
Then the FRCM carbon fiber mesh is troweled into CM



Press grid into CM and trowel over



The final CM coat is about 1/4” thick



Finished Surface

This recent article is available at Structuremag.org

Seismic Repair and Retrofit in Alaska

Mar, 2023 By Ellen Hamel P.E., S.E In Feature

Gruening Middle School, located in Eagle River, Alaska, was significantly damaged during a magnitude 7.1 earthquake on November 30, 2018. The epicenter of the earthquake was only 11 miles from the school. Due to the damage, Gruening was shut down for almost three years for earthquake repair, seismic upgrades, and programming upgrades. The Gruening Middle School Earthquake Recovery Project was an important effort by the Anchorage School District (ASD) to repair and upgrade the almost 40-year-old school (*Figure 1*). The project was a success thanks to committed team members and the first use of Simpson Strong-Tie (Simpson) Fabric-Reinforced Cementitious Matrix (FRCM) in Alaska.

Napa Valley Courthouse used FRCM for strengthening

Napa County Courthouse Case Study – Seismic Upgrade

- Building damaged in 2014 Napa earthquake (6.0 magnitude)
- Structural damage to unreinforced masonry and brick walls
- EOR – ZFA Structural Engineers
- Construction methods considered were shotcrete, FRP, FRCM, mortar repointing, grout injection and replacement with CMU walls

INTERNATIONAL CONCRETE REPAIR INSTITUTE
1000 WESTGATE DRIVE, SUITE 252
ST. PAUL, MINNESOTA 55114 USA
P: +1 651-366-6095 | E: INFO@ICRI.ORG | WWW.ICRI.ORG

Napa County Courthouse – What FRCM Provided?

- FRCM provided in-plane and out-of-plane strengthening with minimum surface preparation beyond the removal of existing finishes
- The FRCM is also detailed to engage and tie the historic masonry to the new CMU walls
- Cement based FRCM did not seal the historic walls and allowed the walls to breathe as it has for 150 years and provided a favorable surface for installation of plaster finishes

Structural FRCM Repairs – Structural Drawings

REPAIR SCHEDULE	
REPOINT	REPOINT CRACKED MORTAR JOINTS EXCEPT WHERE GROUT INJECTION OR FIBER REINFORCED CEMENTIOUS MATERIAL IS SPECIFIED
GROUT INJECT	GROUT INJECT ALL CRACKS 1/16" IN WIDTH OR GREATER UNO ON ELEVATIONS
BRICK RECONSTRUCTION	IF SPALL AREA IS LESS THAN 16" SQUARE AND DOES NOT EXTEND FULL DEPTH FILL W/ MORTAR, OTHERWISE RECONSTRUCT AREA WITH BRICK. NOTIFY ENGINEER OF RECORD IF AREA EXCEEDS 24" SQUARE
FIBER REINFORCED CEMENTIOUS MATERIAL (FRCM) OVERLAY	AS INDICATED PER PLAN, ELEVATIONS, AND SPECIFICATIONS. GROUT INJECT ALL CRACKS 1/16" OR GREATER BELOW FIBER REINFORCED CEMENTIOUS MATERIAL. REPOINT/GROUT ON FARSIDE OF EXISTING BRICK WALLS WHEN OVERLAY IS INSTALLED ON ONE FACE ONLY
CMU REPLACEMENT	AS INDICATED PER PLANS, ELEVATIONS, AND SPECIFICATIONS

SEE **K/S-0.1** & SPECIFICATIONS FOR ADDITIONAL INFORMATION

STRUCTURAL FRCM REPAIRS				
GRID LINE	FLOOR	THICKNESS	EXISTING CAPACITY	REPAIRED CAPACITY
1	2ND	16"	-	NOMINAL
1.75	2ND	12"	67.5k	90.5k
2	2ND	12"	92.3k	102.5k
4	2ND	8"	55.9k	69.9k
5	2ND	16"	42.7k	51.2k
A	2ND	16" (2)	-	NOMINAL
D	2ND	12"	125.7k	170k
E	2ND	12"	156.8k	174k
H	2ND	16"	-	NOMINAL
3 NORTH	1ST	12"	117.5k	155.3k
3 SOUTH	1ST	12"	122.2k	131.3k
5	1ST	16"	-	NOMINAL
B	1ST	16"	-	NOMINAL
D	1ST	12"	212k	326.3k
E	1ST	12"	212k	326.3k

NOTE:

1. OVERLAY SHALL BE PROVIDED AS SHOWN ON PLAN AND ELEVATIONS (2)
2. SEE **L/S-0.1** FOR ADDITIONAL INFORMATION
3. AT WALLS INDICATED AS "NOMINAL" PROVIDE BIDRICTIONAL OVERLAY AS SOHWN IN ELEVATIONS.

A mockup ensured proper FRCM installation

Before FRCM

After FRCM

Additional articles available at Structuremag.org

Napa County HISTORIC Courthouse PART 3

By Brett Shields, P.E., Luke Wilson, S.E., and Kevin Zucco, S.E.

Figure 1. Entry showing damage taken the morning of the earthquake.

On August 24, 2014, the South Napa Earthquake left the Napa County Historic Courthouse heavily damaged with partially collapsed walls, ceilings, and extensive wall cracking (*Figure 1*). The City of Napa red-tagged the courthouse as unoccupiable, which began the extensive damage documentation and repair effort. The overarching goal throughout this process was to provide a solution to repair and preserve as much of the historic building as practical while providing improved detailing.

The historic courthouse building is a 140-year-old, two-story, unreinforced brick bearing wall structure with wood-framed floors and roof, located in downtown Napa. The building had a significant remodel and retrofit in 1977 which included concrete frames for new openings, concrete or concrete masonry unit (CMU) infill of existing openings, and many other small renovations.

Figure 2. FRCM uni-directional (left), bi-directional (right).

The observed earthquake damage in the brick walls varied from miscellaneous small cracks to significant cracking with permanent in-plane and out-of-plane displacements in both principal directions, to the partial collapse of wall sections. The repair approach needed to provide a similarly diverse set of options to match observed conditions. Traditional brick repair methodologies, repointing, and grout injection were used in areas of minor damage where appropriate. Complete wall reconstruction using specially detailed CMU was used in areas with permanent deflections and partial collapse. However, a third repair approach was needed to address the majority of wall areas exhibiting extensive cracking and minimal displacement. The product requires surface preparation to receive a base coat for finished plaster. The epoxy-based resin creates a sealed surface over the historic brick, restricting the brick's natural ability to breathe. Maintaining this breathability was critical for the preservation of the historic brick.

During concept design, an overlay product used extensively in Europe, Fabric-Reinforced Cementitious Matrix (FRCM), was being introduced to the California market by manufacturers including Simpson Strong-Tie. FRCM consists of either uni-directional or bi-directional carbon fiber fabric (*Figure 2*) embedded between lifts of cementitious matrix installed in ¼- to ½-inch lifts. The lifts can either be installed by hand similar to plaster, or as a spray installation similar to shotcrete. The fabric, which comes in rolls up to 77 inches wide, is pressed into the base lift before having a cover lift of matrix installed. The total thickness for one layer of FRCM is approximately 1 inch plus ½ inch for each additional layer of FRCM. As a porous cementitious material, FRCM is more homogeneous with existing brick stiffness and mechanical properties compared to epoxy-based overlays and allows the historic brick to breathe. The FRCM surface preparation only requires a surface clear of loose debris, cleaned, and saturated surface dry for cementitious matrix adhesion and curing. The FRCM can double as the base coat for plaster installation, removing an extra preparation step required for FRP.

The FRCM, combined with grout injection of large cracks in the brick substrate, was used to restore in-plane capacity to extensively cracked

Figure 1. Rendering. Courtesy of Rowell Albrecht & Associates.

Seismic Retrofit of the Atascadero Printery

By Allan van Enckevort, S.E.

On December 22nd, 2003, the San Simeon Earthquake shook the central California coast damaging two historic unreinforced masonry buildings in downtown Atascadero. One of those buildings was The Printery, constructed in 1915 to house E.G. Lewis' (the Founder of the Colony of Atascadero) printing operation. Since the earthquake, the building has been abandoned and has suffered from vandalism over the years. In 2016, FTF Engineering was introduced to a non-profit looking to purchase the building to transform it into a community arts building (*Figure 1*). The non-profit, operating as The Printery Foundation, was able to secure ownership of the building from a public auction in 2017.

The building was designed by Bliss and Faville Architects out of San Francisco and Engineer M.C. Couchot out of Oakland. The main portion of the building is a rectangular-shaped 2-story structure with a partial basement. At the rear is an original single-story room that housed the printing press and another single-story annex, constructed later, used as a gymnasium for a boy's home tenant (*Figure 2*). The foundation, basement, and second floor are of concrete construction with ½-inch-square smooth bar reinforcing with unreinforced brick masonry bearing walls. The first story walls are 4-wythes-wide, and the second story walls are 3-wythes. Roof framing in the two-story section consists of wood rafters spaced at 2 feet on-center, trussed with 1x bottom chords and webs with the hips supported on a steel truss at each end. The single-story portions have hipped roofs framed with long-span steel trusses and wood rafters between. Currently, the buildings are topped with metal roofing over straight sheathing, though there is a reference to a mission tile roof in the as-built drawings.

In 2000, the building was nominated for the National Register of Historic Places and was officially added in 2004. The prominent historical features of the building include the Italian Renaissance terra

Figure 2. Existing floor plan.

California project used FRCM for repair

Surface prep is the key..


United Rentals

FRCM QA and QC

Field Test: ASTM C1583

- Pull-off tests shall be conducted on an area adjacent to strengthening locations
- Adhesion test should exceed 200 psi
- When failure is at grid-matrix interface, strength computed on net matrix area should be at least 400 psi

Failure at substrate

Failure at matrix

Lab Test

Lab Test with Mortar Cubes: ASTM C109

Lab Test with Witness Panels: AC 434 Annex A

Bond Tests were performed

Test No.	Location	PSI	Notes
1	Level B2, A line between 8 and 9 lines	200 psi	No failure in core
2	Level B2, A line between 8 and 9 lines	200 psi	No failure in core
3	Level B2, A line between 8 and 9 lines	200 psi	No failure in core
4	Level B2, A line at 5 line	350 psi	No failure in core
5	Level B2, A line between 6 and 7 lines	200 psi	No failure in core
6	Level B2, A line between 6 and 7 lines	200 psi	No failure in core
7	Level B1, A line at 5 line	200 psi	No failure in core
8	Level B1, A line between 5 and 6 lines	180 psi	Failure within substrate at 7/8 to 1 inch
9	Level B1, A line between 6 and 7 lines	200psi	No failure in core

Questions?

Aniket Borwankar
Senior Development Manager
Composite Strengthening Systems
Simpson Strong-Tie
(415) 310-5374
aborwankar@strongtie.com