Seismic retrofit of structural elements with FRCM prior to recent earthquakes in Italy: What happened to them?

Dr. G. Mantegazza
Technical and R.& D. Manager
RUREDIL Spa
PBO + CARBON = Cementitious Matrix
CARBON + Epoxy Resin = FRP

FRCM
Milan Soccer Stadium - Italy

Beams Shear reinforcement of first ring
Cooling Towers

Thermal Power Plant (Germany)
FRCM Components

Carbon
+
Cement-based Adhesive
=
C- FRCM
FRCM Components

PoliparafenilenBenzobisOxazolo (PBO) + Cement-based Adhesive = PBO- FRCM
FRCM: Fiber Reinforced Cement Matrix

A composite system for structural strengthening:
• High strength mesh works as continuous reinforcement
• Cement-based adhesive anchors the mesh to the concrete support
• One or more sheets of mesh are used so as to reach the requested load increase
Components At –A- Glance

<table>
<thead>
<tr>
<th>PBO fiber mesh reinforcement</th>
<th>Cement-based adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Fiber</strong></td>
<td><strong>Ultimate Tensile Strength ksi (MPa)</strong></td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td><strong>PBO</strong></td>
<td>840 (5,800)</td>
</tr>
<tr>
<td><strong>Carbon</strong></td>
<td>550 - 700 (3,500 - 4,800)</td>
</tr>
<tr>
<td><strong>Aramidic (Hi-Mod)</strong></td>
<td>290 - 400 (2,000 - 2,800)</td>
</tr>
<tr>
<td><strong>Glass</strong></td>
<td>220 - 500 (1,500 - 3,500)</td>
</tr>
</tbody>
</table>

PBO performance characteristics are superior to carbon
According to AC434, FRCM tensile properties evaluated include:

- Tensile modulus of elasticity of un-cracked specimen, \( E_f^* \)
- Tensile modulus of elasticity of cracked specimen, \( E_f \)
- Ultimate tensile strain, \( \varepsilon_{fu} \)
- Ultimate tensile strength, \( f_{fu} \)
- Tensile strain corresponding to transition point, \( \varepsilon_{ft} \)
- Tensile stress corresponding to transition point, \( f_{ft} \)

Listed properties extracted from idealized graph resulting from experiment.
Characterization – Typical Tensile Properties

PBO Tension Specimens

Axial Stress, $f_a$ (MPa)

- $f_{fr} = 237$ MPa
- $\varepsilon_{fr} = 0.00014$
- $f_{fu} = 1060$ MPa
- $\varepsilon_{fu} = 0.0065$
- $E_f = 137,400$ MPa
- $E^* = 1,550,000$ MPa

Axial Strain, $\varepsilon_a$ (mm/mm)

$A_f = 2.34$ mm$^2$
Characterization – FRCM vs. FRP Failure Mode Comparison

FRCM failure is by pullout of the fibers

FRP failure is by breakage of the fibers
Material Characteristics of PBO FRCM Composite System

This strengthening system must be designed to meet specific project design requirements. As design guide, follow ACI 549.4R-13 “Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures”.

Performance characteristics of the composite were tested by ICC-ES accredited Lab in accordance to AC434 so as to satisfy ACI 549.4R-13 Design Guidelines

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>SYMBOL</th>
<th>UNIT</th>
<th>MEAN</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>$f_{fu}$</td>
<td>ksi (MPa)</td>
<td>241.34 (1664)</td>
<td>11.17 (77)</td>
</tr>
<tr>
<td>Ultimate Tensile Strain</td>
<td>$\varepsilon_{fu}$</td>
<td>mm/mm</td>
<td>0.0176</td>
<td>0.0013</td>
</tr>
<tr>
<td>Modulus of Elasticity of Cracked specimen</td>
<td>$E_f$</td>
<td>msi (GPa)</td>
<td>18.51 (127.65)</td>
<td>2.22 (15.32)</td>
</tr>
</tbody>
</table>
Product Highlights

• ICC-ES ESR-2013 listed product.

• Level of reinforcement is comparable to Fiber Reinforced Polymer (FRP) that uses carbon fiber and epoxy resin as adhesive.

• Level of strengthening can be customized through the application of one or more plies of PBO Fabric.

• Once applied the composite does not alter the response to fire of steel reinforced concrete and therefore fire protection is not required, even for indoor applications.
Material Characteristics of carbon FRCM

This strengthening system must be designed to meet specific project design requirements.

As design guide, follow ACI 549.4R-13 “Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures”.

Performance characteristics of the composite were tested by ICC-ES accredited Lab in accordance to AC434 so as to satisfy ACI 549.4R-13 Design Guidelines.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>SYMBOL</th>
<th>UNIT</th>
<th>MEAN</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>$f_{fu}$</td>
<td>ksi (MPa)</td>
<td>149.53 (1031)</td>
<td>7.83 (54)</td>
</tr>
<tr>
<td>Ultimate Tensile Strain</td>
<td>$\varepsilon_{fu}$</td>
<td>mm/mm</td>
<td>0.0100</td>
<td>0.0014</td>
</tr>
<tr>
<td>Modulus of Elasticity of Cracked specimen</td>
<td>$E_f$</td>
<td>msi (GPa)</td>
<td>11.56 (79.73)</td>
<td>2.67 (18.44)</td>
</tr>
</tbody>
</table>
Product Highlights

• ICC-ES ESR-2013 listed product.
• Level of strengthening can be customized through the application of one or more plies of C-FRCM.
• Once applied the system does not alter the response to fire of masonry construction and therefore fire protection is not required, even for indoor applications.

• Durable in conditions of high ambient temperature since the system is not characterized by glass transition temperature limitations.
Guide to Design and Construction of Externally Bonded Fabric-Reinforced Cementitious Matrix (FRCM) Systems for Repair and Strengthening Concrete and Masonry Structures

Reported by ACI Committee 549
ACCEPTANCE CRITERIA FOR MASONRY AND CONCRETE STRENGTHENING USING FIBER-REINFORCED CEMENTITIOUS MATRIX (FRCM) AND STEEL REINFORCED GROUT(SRG) COMPOSITE SYSTEMS

AC 434

Approved on June 2016
L’AQUILA EARTHQUAKE

April 6th 2009
Project: Church of Santa Maria di Centurelli –Caporciano (AQ) – ITALY

Amenities: The rural church was built in 1558. It is an ancient transit route for shepherds towards the city of L'Aquila, from the renaissance age. Geographical position, structure of the church, vaults.

Owner: Vatican City State Heritage

Contractor: Italian Artistic Heritage Authority

Consulting Engineering (Architecture): Franco De Vitis – Architect

Consulting Engineering (Structure): Carlo Grande – Engineer

Year: 2003
Project area: 540,000 ft²
Building area: 355,200 ft²
Cost of the project: 700,000 €

Strengthening Surface: 6,500 ft² C-FRCM
Seismic retrofitting of the vaults made with FRCM

Church of Santa Maria di Centurelli Caporciano (AQ)
Caporciano is located 12 mi from L’Aquila
Seismic wave direction
Damage due to earthquake
EMILIA ROMAGNA EARTHQUAKE
May 12th 2012
Project: Chapel of S. Francesco–ROLO (PC) – ITALY- Seismic retrofitting Oratory, Structure of the church and vaults.

Owner: Vatican City State Heritage

Contractor: Regional Christian Dept. Of Rolo - Italy


Consulting Engineering (Structure): Eng. Poli –ESATECNA Consulting (Reggio Emilia)

Year: 2011
Project area: 43.100 ft²
Building area: 3.300 ft²
Cost of the project: 100.000 €
Strengthening Surface: 3.770 ft² C-FRCM
Seismic retrofitting of the vaults
MADE WITH FRCM
YEAR 2011
ORATORY CHAPEL - ROLO (RE)

The Rolo municipality is located in the earthquake crater.
ORATORY CHAPEL - ROLO (RE)

The Rolo municipality is located in the earthquake basin
The chapel is located in the red zone, a restricted area with a lot of collapsed buildings.
Absence of cracks on the vaults reinforced with FRCM
CENTER OF ITALY- EARTHQUAKE

August 24th 2016
Project: Regional State Highway Viaduct - Location Posta (Rieti)- Italy
Seismic retrofitting of columns and beams

Owner: ANAS ITALIAN NATIONAL HIGHWAY AUTHORITY

Contractor: ANAS ITALIAN NATIONAL HIGHWAY AUTHORITY

Consulting Engineering: Technical Office - Rieti’s County

Year: 2015
Project area: 323.917 ft²
Building area: 269.097 ft²
Cost of the project: 2.200.000 €
Strengthening Surface: 22.640 ft² PBO-FRCM
Viaduct 70° mile - Location Posta (Rieti)

Structural Repair with FRCM systems MADE IN 2015
The viaduct is located in POSTA (Rieti)

17 mi distance from Amatrice
ANAS ROMA – ITALIAN NATIONAL HIGHWAY AUTHORITY

They made a survey after the earthquake and they noted

NO DAMAGE    NO CRACKS

AFTER THE EARTHQUAKE
NORCIA EARTHQUAKE

October 30th 2016
Project: Regional State Highway - Masonry bricks bridge  
Location Abbazia di Fiastra Tolentino- Macerata Italy

Owner: ANAS ITALIAN NATIONAL HIGHWAY AUTHORITY

Contractor: ANAS ITALIAN NATIONAL HIGHWAY AUTHORITY

Consulting Engineering: Technical Office. Macerata’s County

Year: March 2016
Project area: 215.278 ft²
Building area: 161.458 ft²

Cost of the project: 1,300,000 €
Strengthening Surface: 12.917 ft² C-FRCM
Masonry bricks bridge with arches on three span
Location: Abbazia di Fiastra – Tolentino (Macerata)
Location Fiastra – Tolentino (Macerata)  
About 40 miles from Norcia – Central earthquake location
No damage, No cracks or other structural effects coming from the earthquake has been reported by Regional Highway Authority.
Thank you!
Questions