Tecniche di rinforzo con materiali compositi appropriati alle costruzioni storiche
Tecniche di rinforzo con materiali compositi appropriati alle costruzioni storiche

1) Uno sguardo alle applicazioni pionieristiche

Motivazioni per una diffusione!

1) Valore molto basso dei rapporti peso/rigidezza e peso/resistenza
2) Durabilità e ridotta manutenzione
SE SI RISPETTA IL LIVELLO DI QUALITÀ RICHIESTO PER LA TECNOLOGIA

2) La possibilità di preservare la concezione strutturale originale della costruzione aumentando la prestazione strutturale del materiale storico durante le azioni esterne eccezionalmente severe.
Contrastare l’insorgere di meccanismi di collasso durante le azioni esterne eccezionali (terremoti, bufere, nevicate, impatti, etc.).

Tecniche per la muratura storica:

1) Placcaggio appropriato (Appropriate plating) o Cinturazione (Belting)

2) Ristilatura armata (Reinforced Re-pointing)

3) Rivitalizzazione dei giunti di letto (bed joint re-vitalisation) (FOR RE-CONSTRUCTION).
FUNDAMENTAL TECHNIQUES FOR HISTORICAL CONSTRUCTION STRENGTHENING with FRP or FRCM

Deliceto

cFRP glued
cFRCM
cFRP
cFRCM

PLATING

REPOINTING

BED JOINT REVITALIZING

FRP or FRCM

FRP

FRCM

PLACCAGGIO

RISTILATURA

RIVITALIZZAZIONE DEL GIUNTO
BELTING THE DRUM of the dome
Church Panaghia Faneromani
Aegeon (Grecia), 1996.

DRIVING ASPECTS
Aggressive environments
(No weight increase)
COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON SOME PIONEERING EPISODES

Masonry Building
Zurich (Switzerland), 1996.

Application on vertical masonry wall

Previous timber decks substitution and elevator walls braced with cFRP Laminae
Cathedral Città di Castello (Perugia, Italia),

May 1997,
Belting Dome with cFRP.

PLATING / BELTING TECHNIQUE

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON SOME PIONEERING EPISODES

NEO-GOTHIC CROSS VAULTS OF THE NAVE

“BRICK RAIN”


1997 PLATED IN EXTRADOS

gFRP
1997 Sept 26th strong earthquake in Umbria, several interventions on the Basilica of San Francesco in Assisi with cFRP and aFRP to sustain the partial collapsed gothic cross vaults.

Collapsed vaults, 1997

- GLUE-LAM;
- MULTIDIRECTIONAL aFRP;
- PULTRUTED GLASS BARS;
COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON SOME PIONEERING EPISODES

1999/2000: Giubileo
reduction of vulnerability of huge cracked gothic vaults

technique of appropriate plating in extrados of all principal nave vaults.

All tie-rods deviated in compression

Basilica di San Petronio

Continuous crack in extrados along all the nave

cFRP appropriate plating
Dynamic, II mode

Static horizontal forces (10% vertical w.)

Roman Arch in Rimini

FRCM plating first ring.

Cementitious matrix and reinforcing carbon net.

To contrast collapse mechanisms (15)

Re-construction of Roman Arch, ancient Rimini gate

Bed Joint Revitalising

cFRM carbon Fiber Reinforced Matrix

COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: A LOOK ON SOME PIONEERING EPISODES
COMPOSITES TECHNIQUE APPLIED TO HISTORICAL CONSTRUCTIONS PROTECTION: a look on some pioneering events

RE-CONSTRUCTION

NOTO (SICILIA, ITALIA) CATHEDRAL

Reconstruction 1996-2007 of collapsed parts of Noto Cathedral (Sicilia, Italia) utilized

1) plating of arches covering principal nave and

2) bed joints re-vitalising with cFRCM in both applications.
before

NOTO 1996
If it is possible to build *where it was*, I do not think is possible to built *as it was*.

“Se è possibile costruire *dov’era*, non credo sia possibile costruire *com’era*”

ALDO ROSSI

Colonne com’erano !!!?
Re-construction of collapsed Noto Cathedral (Sicilia, Italia) utilized *plating* of arches covering principal nave
**Re-construction** of collapsed Noto Cathedral (Sicilia, Italia) utilized *bed joints re-vitalising* with cFRCM in both applications..
Chiesa di s. Maria di Paganica AQ

Idea and project:
Ing. Luciano Marchetti e Prof. Salvatore Russo (con Ing. A. Adilardi e Arch. G. Boscato)
TIPOLOGIE DI COMPOSITI ADATTI PER RINFORZARE LE COSTRUZIONI STORICHE

Fiber Reinforced Polymer (FRP)
Fiber Reinforced Cementitious Matrix (FRCM)
Textile Reinforced Mortar (TRM)
Steel Reinforced Grout (SRG)

Composites as mechanism inhibitors
COMPOSITE MATERIAL

Matrix + Reinforcement

Polymeric

FRP

Traditional

Innovative

FRCM

Cementitious

Mineral

Fibers

Innovative solutions

Fabrics

PBO, UHTSS, BASALT

Vegetal

Bio-composites

trend
COMPOSITE

REINFORCEMENT of composite

continuous

FIBERS

MONO-DIRECTIONAL

Pseudo-TESSUTO
Pseudo FABRIC

BI-DIRECTIONAL

Trama e ordito TESSUTO
weft and warp FABRIC

MULTI-DIRECTIONAL

INORGANIC

STEEL
METALLIC

CARBON
MINERAL

GLASS

ARAMID
ORGANIC

PBO, PVA...

FLAX

VEGETAL
PBO Fibers

*Poliparafenilen-Benzo-bisOxazolo (PBO)*

Developed by TOYOBO Co. Japan named Pbo Zylon®.

- Toughness, high modulus, resistance to abrasion, fire, UVA
- Better than Aramidic fibers. Low humidity absorption (0.6%).

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>DENSITY [kg/m³]</th>
<th>ELASTIC MODULUS [GPa]</th>
<th>TENSILE STRENGTH [MPa]</th>
<th>RUPTURE ELONGATION [%]</th>
<th>CRITIC TEMPERATURE [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBO</td>
<td>1560</td>
<td>270</td>
<td>5800</td>
<td>2.15</td>
<td>650</td>
</tr>
</tbody>
</table>

SINTETIC

*Co-valent Link with cement matrix*
STEEL wires

Initials: UHTSS  acronym: Ultra High Tensile Strength Steel
small wires assembled with torsion arranged in fabrics.

Composites
SRG (Steel Reinforced Cement-Grout)
SRP (Steel reinforced Polymer)
patented by HARDWIRE,
Reinforcement GOODYEAR used for pneus

Steel fabrics

Pseudo-fabrics (monodirectional):

a) Low (4 trefoli / inch);
b) Medium (12 trefoli / inch);
c) High (23 trefoli / inch)
bio-composites,

<table>
<thead>
<tr>
<th>Fibra</th>
<th>Densità (g/cm³)</th>
<th>Carico rottura (MPa)</th>
<th>Costo relativo (dollari /kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbonio</td>
<td>1,8</td>
<td>1700-2400</td>
<td>220</td>
</tr>
<tr>
<td>vetro</td>
<td>2,5</td>
<td>1400-2500</td>
<td>5</td>
</tr>
<tr>
<td>lino</td>
<td>1,5</td>
<td>900-1200</td>
<td>1.5</td>
</tr>
<tr>
<td>canapa</td>
<td>1,4</td>
<td>400-700</td>
<td>1.3</td>
</tr>
<tr>
<td>juta</td>
<td>1,4</td>
<td>400-600</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Lino=FLAX     Canapa=HEMP     Juta=JUTE
mineral-composite
basalt fibres

- Thermal and acoustic insulating
- Stable at high temperature (ideal for FRCM).
- Chemical resistant in aggressive ambient.

Mineral matrix + basalt fabrics for masonry strengthening !!!

<table>
<thead>
<tr>
<th>Fibra</th>
<th>Conduttività termica (w/m k)</th>
<th>Temperatura fusione (°C)</th>
<th>Resistenza trazione (Mpa)</th>
<th>Moludo elastico (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vetro</td>
<td>0.034-0.04</td>
<td>1120°</td>
<td>3450</td>
<td>77</td>
</tr>
<tr>
<td>Basalto</td>
<td>0.031-0.038</td>
<td>1450°</td>
<td>4840</td>
<td>89</td>
</tr>
</tbody>
</table>
Pseudo-fabric, mono-directional

Same direction

Assembled yarns or rovings

Transversal link

Pseudo-fabric, bi-directional

ASSEMBLED ROVINGS

Mesh/Grid/

steel

a

b

c

multi-directional
FABRICS (textiles)

Trama = weft
TRAMA (engl. WEFT, franch. TRAME, spanish TRAMA).

ORDITO (engl. WARP, french CHAINE,,spanish URDIMBRE)
Ordito = warp
Set of longitudinal yarns in which the transversal wires are inserted.
MATRIX of composite

CEMENT BASED (GROUT)

FRCM Fiber Reinforced Cementitious Matrix

POLYMERIC (RESIN)

FRP Fiber Reinforced Polymer
A and B components of epoxy resin

Hand-process

In Lab

Impregnation of fabric

In-situ

Matrix Preparation

Roller
1. SUPPORT MATERIAL
2. FIRST LAYER OF MATRIX
3. MESH OF FIBER (pboFRCM)
4. SECOND LAYER OF MATRIX
5. SECOND MESH OF FIBER (opzionale)
6. THIRD LAYER OF MATRIX
COLLASSO DEL COMPOSITO

MECCANISMI PECULIARI DI CRISI
Dipendenti da natura della matrice e delle fibre e dall’accoppiamento
**FRCM: Meccanismo di collasso**

**TEST:** PULL OUT of **ROVING**

Adesione dei filamenti esterni del roving alla matrice:
C moderata  PBO forte

I filamenti interni al roving rimangono asciutti e durante il collasso cedono ed esibiscono dissipazione energetica per attito
Materiale del supporto + FRCM

Meccanica del collasso

ASPETTI GENERALI

Delaminazione
- Nel supporto

Distacco alla interfaccia

Scorrimento delle fibre

Delaminazione
- Nel pacchetto composito

Representation from F. Focacci et al.
Some Experimental tests at IUAV UNIVERSITY of VENICE
SIMULATION OF WALL SUBJECTED TO AXIAL PERMANENT LOAD AND TRANSVERSAL VARIABLE LOADING $P$
<table>
<thead>
<tr>
<th>Sezione trasversale</th>
<th>I° investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>M10Da (F= 10 kN)</td>
<td>a: M10Da (F= 10 kN)</td>
</tr>
<tr>
<td>M10Sa+T (F= 10 kN)</td>
<td>b: M10Sa+T (F= 10 kN)</td>
</tr>
<tr>
<td>M5Da (F= 5 kN)</td>
<td>c: M5Da (F= 5 kN)</td>
</tr>
<tr>
<td>M5Sa+T (F= 5 kN)</td>
<td>d: M5Sa+T (F= 5 kN)</td>
</tr>
<tr>
<td>M10</td>
<td>e: M10 (F= 10 kN)</td>
</tr>
<tr>
<td>M5</td>
<td>f: M5 (F= 5 kN)</td>
</tr>
</tbody>
</table>

**Load P (daN)**

**Displacement (mm)**
OBIETTIVO: “RITardare” o “INIBIRE” il meccanismo di collasso durante azioni eccezionalmente severe non modificando i meccanismi resistenti in condizioni ordinarie di servizio ossia rispettando il funzionamento statico di progetto.
Kythira Greece 2995

COLLASSO DI TORRI: MECCANISMI

Majano UD
Il meccanismo di collasso divide la struttura di muratura compatta (solida e robusta) in BLOCCHI RIGIDI integri.

La muratura a doppia foglia (senza diatoni) Manifesta DE-FOLIAZIONE.

Strutture di muratura
Terremoto

S. GIULIANO DI PUGLIA (CB Italia) 2002

Strutture di muratura
Terremoto

PIETRA

S. GIULIANO DI PUGLIA (CB Italia) 2002

Solid and robust masonry

ABRUZZO 2009

Mattone

BAGNOLO IN PIANO (RE Italia) 1996

EMILIA 2012

ERRORS
DISLOCATION A

DISLOCATION B

LOCAL DAMAGE BY KEY OF INTERN. TIE-ROD

RENO CENTESE (CENTO)

DIAGONAL CRACKING AND SLIDING
CAVEZZO
MECCANISMO TIPICO
RIDUZIONE IN BLOCCHI
INTERNAMENTE INTEGRI

CONTRASTO NEL PIANO DI VIBRAZIONE
Mineral-composites,

Culture and technicality

Demolition (partial)
Chimney in Ferrara
Faculty of Eng

Demolition (partial)
Chimney in Bologna

Compound resulting from inorganic process (of nature)

EMBALMED ARCHITECTURE !!!

ITALIAN
Negative history

cFRCM

chimney
Sawmill CUNY
Gerardmer, France.
Wrapping for strengthening
OBIETTIVO: “Ritardare” o “INIBIRE” il meccanismo di collasso durante azioni eccezionalmente severe non modificando i meccanismi resistenti in condizioni ordinarie di servizio ossia rispettando il funzionamento statico di progetto.
**Intervention to reduce vulnerability by means the contrast of collapse mechanisms**

"Principia"

"Vincula" **CONSTRAINS** to mechanisms of seismic collapse

"Auxilia" **AID** for resisting to seismic actions;

no **STRUCTURAL change** for frequent loadings (verticals)
ARCH (AND VAULTS) STRENGTHENING

**STRENGTHENING STRATEGY**

- External strengthening (FRP or FRCM) bonded to intrados or to extrados

  - **Partial:** collapse with mechanism
  - **Total:** (collapse for presso-flexure or shear)

Alternate hinges
- Two at intrados
- Two at extrados

Mode I (opening)
- WITHOUT STRENGTHENING
  - SHEAR collapse very rare (thrust line approximately parallel to middle line)

- WITH STRENGTHENING
  - Before the hinge collapse mechanism can appear
  - the shear detachment (sliding joints)

  Thrust line very inclined respect middle line.

Experiments of Bednartz    FRCM strengthening

\[ \lambda_{c} = 0.0366 \]
\[ \lambda_{cR} = 0.202 \]
\[ \lambda_{cR} = 0.2387 \]
Shear collapse

PLATING extrados with FRCM

from Luk Bednartz PhD Thesis Univ WROCLAW
Steel-FRCM

From A. BORRI University of Perugia (Italia) et al. 2006
COMPORTAMENTO SISMICO DELLE CHIESE

ANALISI STORICA DEL DANNO SISMICO

IN COERENZA CON L’APPROCCIO PER MACROELEMENTI

PER STRUTTURE DI MURATURA COMPATTA

CONSIDERAZIONE CON ESCLUSIONE DELLE MURATURE A FOGLIA MULTIPLA\{ Multiple-leaf\}
(cioè A SACCO E A DOPPIA PARETE SENZA DIATONI)

Molise 2002

Abruzzo 2009

Defoliation of masonry
Structural macroelements (architectonically and structurally defined) which have peculiar and recurrent seismic behaviours and their aggregation.

The aggregation lines are not only geometric lines, but they represent the transmission lines of stresses. So, they can be considered structural lines, being fundamental to the definition of the building behaviour.

1) macroelement mechanisms

+ o -

2) disaggregation mechanisms of macroelement each other
DOMINANT SEISMIC DIRECTION

LONGITUDINAL
DOMINANT SEISMIC DIRECTION

LONGITUDINAL

Experimentations and modelings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC.
DOMINANT SEISMIC DIRECTION

LONGITUDINAL

Umbria 1997

Friuli 1976

Macroelement: façade

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC

Daniela Bufo - Università IUAV di Venezia
DOMINANT SEISMIC DIRECTION  
LONGITUDINAL  

Friuli 1976  
Emilia Romagna 1987  
Umbria 1997
Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC

**Longitudinal seismic direction** → **Macroelement façade: segregation mechanism**

Emilia Romagna 1987

Emilia Romagna 1987

Molise 2002

Lombardia 2004
DOMINANT SEISMIC DIRECTION

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC

Emilia Romagna 1987

Friuli 1976
Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC
Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC

**Longitudinal seismic direction** → **segregation mechanism**

Emilia Romagna 1987
DOMINANT SEISMIC DIRECTION

TRANSVERSAL

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC
DOMINANT SEISMIC DIRECTION

TRANSVERSAL

SEISMIC ANALYSIS

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC

Molise 2002

Umbria 1997
DOMINANT SEISMIC DIRECTION

Friuli 1976
Friuli 1976
Emilia Romagna 1987
Emilia Romagna 1987

Umbria 1997
Umbria 1997
Lombardia 2004
Lombardia 2004

SEISMIC ANALYSIS

Macroelement: façade

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC
DOMINANT SEISMIC DIRECTION: TRANSVERSAL

Macroelement: triumphal arch

Friuli 1976

Friuli 1976

Molise 2002

Molise 2002

Emilia Romagna 1987

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC.
DOMINANT SEISMIC DIRECTION

TRANSVERSAL

Emilia Romagna 1987

Molise 2002

Umbria 1997

Emilia Romagna 1987

Lombardia 2004

Lombardia 2004

Nave: segregation mechanism

SEISMIC ANALYSIS

Experimentations and modellings of the collapse seismic limit state of strengthened masonry macroelements with FRP and FRC
The historical analysis of damage according to the macroelement approach is very useful to study complex buildings such as churches;

Each macroelement has peculiar and recurrent seismic behaviour;

The macroelement approach must include the structure evaluation “as a whole”. The comprehension of the interaction between macroelements is crucial;

The aggregation lines among macroelements represent the transmission lines of stresses. In this way, they are not only geometric lines but also structural lines;

Three kind of mechanism can be identified:

1) macroelement mechanism – 2) ”segregation” mechanism between macroelements – 3) mixed mechanism, containing both the previous aspects.
The collapse mechanism of a masonry macroelement is due to the opening of fractures (or fracture lines F.R.) which separate the macroelement in rigid blocks.

Fracture line in MODE I ➔ The fracture line principally causes the blocks detachments

Fracture line in MODE II ➔ The fracture line mainly causes relative *slidings* between blocks
**MODE I**

**Mode Ia:**
relative translation (opening) of blocks

**Mode Ib:**
relative rotation (opening) of blocks with relative rotation centers disposed along the F.L.

**MODE II**

**Mode IIa:**
translation of blocks along their primitive medium plan

**Modo IIb:**
translation of blocks orthogonally to their primitive medium plan
UNIDIRECTIONAL FRP STRIPS ARE APPLIED ORTHOGONALLY TO THE FRACTURE LINES.

MODE Ia: FRP DESIGN

MODE Ib: FRP DESIGN
THE TRANSLATION OF BLOCKS CAN BE AVOIDED BY OVERLAPPING ORTHOGONALLY FRP STRIPS APPLIED DIAGONALLY

CONSIDERING THE MODE IIb, THE USE OF FRP IS NOT FAVOURABLE, BECAUSE OF THE PROBABLE DEBONDING OF THE REINFORCEMENT
CONSIDERING IN PLANE FRACTURES AS SHOWED IN THE PICTURE, FRP STRIPS OUGHT TO BE APPLIED ON THE ENTIRE WALL SURFACE. FOR ALL CASES WHERE THIS SOLUTION IS NOT ALLOWED (DESIGN NOT COMPATIBLE WITH THE RESTORATION RULES OR OTHER IMPOSSIBILITIES DUE TO THE ARCHITECTURAL ORGANISM) THE APPLICATION OF THE STRENGTHENING ON THE TOP OF THE WALL IS A VERY INTERESTING SOLUTION.
THE APPLICATION OF THE STRENGTHENING ON THE EXTRADOS OF THE ARCH IS A VERY EFFICIENT SOLUTION. ON THE OPPOSITE SIDES OF THE STRENGTHENED SURFACE NO HINGES ARE ALLOWED TO FORM. THE NEW COLLAPSE MECHANISM WILL ACTIVATE WITH A GREATER LOAD MULTIPLIER THAN THE PREVIOUS ONE.
INTERAZIONE
TIMPANO DI FACCIATA-TETTO !

Emilia 2012
THE APPLICATION OF FRP STRIPS AS SHOWN IN THE FOLLOWING PICTURES CAN AVOID BOTH IN PLAIN AND OUT OF PLAIN COLLAPSE MECHANISM

D.Bufo (PhD thesis):
3D representation of the façade strengthening design of S.Biagio’s church in Modena
OFTEN, THE MOST EFFICIENT STRENGTHENING DESIGN FOR APSES IS TO ASSURE THE BELTING ACTION. FRP STRIPS CAN BE APPLIED IN DIFFERENT LEVELS ON THE ESTRADOS OF THE MACROELEMENT AND CAN BE COVERED BY PLASTER OR PAINT.

Year 1998  cFRP painted

**CAMOUFLAGE**

PERUGIA – CHIESA DI S. TERESA
By TEC-INN
This project has been executed 2001

Permanent Solution

A. Di Tommaso 2001
L5 Retrofitted “attached” Campanile with cFRP in the Region Marche (Italy). (E.Cosenza et al. 2007)
REPOINTING ARMATO con PIATTINA cFRP + MALTE

Paramenti interni della torre Ghirlandina a Modena

Arch Cadignani COMUNE DI MODENA
TORRE GHIRLANDINA
CUCITURA LESIONI PSEUDO=VERTICALI
Tecnica della ristilatura armata con cFRP

Piattina pultrusa di carbonio come armatura
Malta di calce come intasatura intermedia.
Malta di resina come intasatura terminale.
After seismic collapse to *rebuilt as it was before* It is silly

Dopo il collasso sismico ricostruire come era non è saggio.

The common feeling links the “as it was” only to appearance, then there is possibility to rebuilt strengthening the construction.

Il comune sentire lega il com’era soltanto alla apparenza, vi è spazio di ricostruire rinforzando la costruzione senza modificare la apparenza e il suo funzionamento statico originale in condizioni usuali, riservando una risposta *adeguata* in condizioni eccezionali.
BANDED MASONRY

It. MURATURA LISTATA

SANT JOAN BARCELONA

Madrid

Ss TRINITA’ ABBEY - VENOSA (POTENZA)

Roma

BANDED BRICK MASONRY REINFORCED WITH FRCM

Fig 14  Proposed integrated texture for RECONSTRUCTION: FRCM reinforcing brick band at different level of new masonry

a) Traditional local stone masonry made as before collapse but with stronger mortar
b) Layer of carbon or aramide textile in inorganic matrix
c) New Bricks on strong mortar bed
FUNDAMENTAL TECHNIQUES FOR HISTORICAL CONSTRUCTION STRENGTHENING with FRP or FRCM

Deliceto

cFRP glued

cFRCM

cFRP

cFRCM

PLATING  REPOINTING  BED JOINT REVITALIZING

FRP or FRCM  FRP  FRCM
Dove era come era

Where it was and no how it was

Donde estaba y NON como era

Where it was and seems how it was