Full scale tests on seismic retrofitted existing structures with FRC

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Strengthening of a bridge pier

Case study: existing bridge

Seismic actions

Seismic action

H = 22.40 m  \( V_c = 210 \text{ m}^3 \)  \( V_r = 44 \text{ m}^3 \)
HPFRC

High mechanical performance

Durability

- REPAIRING
- STRENGTHENING
- SEISMIC RETROFITTING

Toughness

Fire resistance

Energy dissipation

Full scale tests on seismic retrofitted structures with FRC
# HPFRC properties

<table>
<thead>
<tr>
<th>Property (specimen dimension)</th>
<th>Standard</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density</td>
<td>UNI EN 12350</td>
<td>2510±2580 kg/m³</td>
</tr>
<tr>
<td>Compressive strength at 1 day (100X100mm)</td>
<td></td>
<td>67 MPa §</td>
</tr>
<tr>
<td>Compressive strength at 7 days (100X100mm)</td>
<td>UNI EN 12390 - 3</td>
<td>111 MPa §</td>
</tr>
<tr>
<td>Compressive strength at 28 days (100X100mm)</td>
<td></td>
<td>131 MPa §</td>
</tr>
<tr>
<td>Compressive strength at 56 days (100X100mm)</td>
<td></td>
<td>&gt;130 MPa</td>
</tr>
<tr>
<td>Cylindrical/Cubical Compressive strength ratio</td>
<td>-</td>
<td>≈ 1</td>
</tr>
<tr>
<td>Flexural strength at 28 days (10X10x400mm)</td>
<td>UNI EN 12390 - 5</td>
<td>18.4 MPa</td>
</tr>
</tbody>
</table>

Stainless steel fibers

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Bridge retrofitting

M-N resistance increase

HPFRC Jacketing

Jaceting thickness: 120 mm

Unreinforced vs. Layer 120 mm:
- $+78\%$ increase
- $+55\%$ increase
- $+74\%$ increase
Experimental set-up

Specimen scaled 1:4

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Concrete pouring

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Original bridge pier

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8
HPFRC jacketing

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Retrofitted pier

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Pre and post retrofitting behavior

Reinforced

Reference (theoretical)

Increment of load bearing capacity (+74%)

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Masonry buildings reinforced with FRC mortar

Ground acceleration

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Strengthening with Fiber Reinforced Mortar

Ground acceleration

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To use thin overlays made of an innovative steel fiber reinforced mortar for:

- improving the out-of-plane resistance of masonry walls (future step of the research);
- enhancing the in-plane shear capacity of the masonry walls.

Experimental tests on walls: aim of the research

Section view of a typical 2-storey URM building

Thin SFRM overlays

Lateral (seismic) load

✓ Floor loads

✓ Ground acceleration

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Material properties: solid clay brick masonry

**Mortar for masonry joints (M2.5 – according Eurocode 6)**
- Flexural strength (according EN 1015-11, 2007) \( 1.5 \text{MPa} \)
- Compressive strength (according EN 1015-11, 2007) \( 4.2 \text{MPa} \)

**Solid clay bricks**
- (size: 23x11x5cm³)
- Flexural strength \( 1.72 \text{MPa} \)
- Compressive strength (EN 772-1, 2002) \( 12.4 \text{MPa} \)
- Tensile strength \( 0.9 \text{MPa} \)

**Composite solid clay MASONRY** (Masonry specimens : 71x48x23cm³)
- Elastic modulus (EN 1052-1, 2001) \( E_m = 4200 \text{MPa} \)
- Compressive strength (EN 1052-1, 2001)

Different bed joint orientations (0°, 22.5°, 45°, 90°)

- \( f_{m,0°} = 6.1 \text{MPa} \)
- \( f_{m,90°} = 5.7 \text{MPa} \)
- \( f_{m,22.5°} = 2.6 \text{MPa} \)
- \( f_{m,45°} = 4.0 \text{MPa} \)
Volume fraction $V_f = 0.82\%$

<table>
<thead>
<tr>
<th>LUNGHEZZA $L_f$ [mm]</th>
<th>DIAMETRO $\Phi_f$ [mm]</th>
<th>RAPPORTO D'ASPETTO $L_f/\Phi_f$ [-]</th>
<th>RESISTENZA A TRAZIONE [MPa]</th>
<th>FORMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.40</td>
<td>38</td>
<td>$&gt; 2400$</td>
<td>Uncinate</td>
</tr>
</tbody>
</table>

Resistenza a trazione per flessione media (a) $(EN\ 1015-11,2007)$ → 6MPa

Resistenza a compressione media (b) $(EN\ 1015-11,2007)$ → 48.3MPa

Valore medio modulo elastico $(EN\ 12390-1)$ → 33600MPa

Resistenza a trazione $(EC2)$ → 3.85MPa
Test instrumentation

DRIFT (%) = \frac{\text{LATERAL DISPLACEMENT}}{\text{WALL HEIGHT}}

Lateral displacement = difference between F1 and B

Wall height = 2070 mm
Experimental set-up

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### Experimental results

#### Load-displacement envelopes comparison

<table>
<thead>
<tr>
<th>Specimen type and loading direction</th>
<th>Lateral load [kN]</th>
<th>First cracking load [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW1</td>
<td>+ 166</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>- 147</td>
<td>60</td>
</tr>
<tr>
<td>MW3 ST-SP</td>
<td>+ 221 &gt;33%</td>
<td>130 &gt;100%</td>
</tr>
<tr>
<td></td>
<td>- 215 &gt;46%</td>
<td>150 &gt;150%</td>
</tr>
<tr>
<td>MW4 ST-LP</td>
<td>+ 232 &gt;39%</td>
<td>211 &gt;225%</td>
</tr>
<tr>
<td></td>
<td>- 219 &gt;49%</td>
<td>202 &gt;237%</td>
</tr>
<tr>
<td>MW5 STK-LP</td>
<td>+ 222 &gt;34%</td>
<td>185 &gt;185%</td>
</tr>
<tr>
<td></td>
<td>- 212 &gt;44%</td>
<td>212 &gt;253%</td>
</tr>
<tr>
<td>MW6 ST-SP</td>
<td>+ 248 &gt;49%</td>
<td>211 &gt;225%</td>
</tr>
<tr>
<td></td>
<td>- 221 &gt;50%</td>
<td>193 &gt;222%</td>
</tr>
</tbody>
</table>

**Central image:**

- **Increment of the first cracking load with respect to MW1**
- **Lateral strength increment with respect to MW6**

**Graphical data:**

- **Displacement [mm]**
- **Load [kN]**

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Simulation of a full-scale masonry building: shaking table test results

Base shear vs. top lateral displacement

Envelope of the cyclic curve

Damage pattern at failure
Numerical modelling of full-scale building

Building 2

Shell elements
MASONRY WALL + MORTAR (CQ40L)

STONE MASONRY & BIOGLOB® MORTAR

Smeared Crack Model
(Total Strain Rotating Crack Model)
Curved Shell Layered Element

F_{V1} = 4.49 N/mm
F_{V2} = 2.39 N/mm
F_{V3} = 20.55 N/mm
F_{H1} = 1582.35 N
F_{H2} = 3183.5 N
F_{H3} = 468.3 N

Traction
Compression

Nonlinear tension softening
Parabolic compression curve
Numerical simulation of the masonry building without coating

Load-Displacement Curves

- Experimental – URM
- Numerical – URM

Positive direction

Negative direction

Numerical and experimental damage patterns comparison

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Test on a full scale masonry building

SFRM coating on the external surface

**STRUCTURE**
- Hollow clay brick masonry
- Wooden floors and roof
- Seismic floor diaphragms

**LOADS**
- Quasi-static reverse cyclic test

**REINFORCEMENT**
- 25 mm thick
- Anchored in foundations
Building characteristics

TYPE OF BRICKS

Poroton P600:
- thickness 200mm
- holes 60%

HORIZONTAL LOADS CONDITION

Proportional to floor mass

OPENINGS CONFIGURATION

1 door + 8 windows

REPRESENTATION OF AN EXISTING BUILDING
Preliminary designs

STRONG WALL

- $H = 12$ m
- $F_h = 1500$ kN

RC FOUNDATION

- $M_{max} = 18000$ kNm

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Test setup and protocol

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Experimental results

CYCLIC RESPONSE OF UNSTRENGTHENED BUILDING

<table>
<thead>
<tr>
<th></th>
<th>Positive loading direction</th>
<th>Negative loading direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S$ [kN/mm]</td>
<td>134</td>
<td>128</td>
</tr>
<tr>
<td>$V_{cracking}$ [kN]</td>
<td>120</td>
<td>128</td>
</tr>
<tr>
<td>$V_{peak}$ [kN]</td>
<td>180</td>
<td>179</td>
</tr>
<tr>
<td>$\delta_{peak}$ [kN]</td>
<td>2.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

FAILURE MODE:

- In-plane longitudinal walls response
- Diagonal shear failure of masonry piers at ground floor

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Experimental vs numerical results

LATERAL LOAD – DISPLACEMENT ENVELOPE

Numerical initial stiffness closed to the experimental one
First cracking and maximum numerical loads slightly underestimated

<table>
<thead>
<tr>
<th>Load</th>
<th>Experimental</th>
<th>Numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+_{S}$ [kN/mm]</td>
<td>134</td>
<td>129 (-4%)</td>
</tr>
<tr>
<td>$K^-_{S}$ [kN/mm]</td>
<td>128</td>
<td>153 (+20%)</td>
</tr>
<tr>
<td>$V^+_{cracking}$ [kN]</td>
<td>120</td>
<td>114 (-5%)</td>
</tr>
<tr>
<td>$V^-_{cracking}$ [kN]</td>
<td>128</td>
<td>112 (-12%)</td>
</tr>
<tr>
<td>$V^+_{peak}$ [kN]</td>
<td>180</td>
<td>147 (-18%)</td>
</tr>
<tr>
<td>$V^-_{peak}$ [kN]</td>
<td>179</td>
<td>145 (-19%)</td>
</tr>
</tbody>
</table>

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Experimental vs numerical results

CRACK PATTERNS AT THE END OF EXPERIMENTAL TEST (inside view of east façade at ground floor):

FAILURE MODE:
- Diagonal shear failure of central pier (Pier 2)
- Rocking mechanism of the external piers (Pier 1 and Pier 3)
- Incipient diagonal shear crack of Pier 1

TENSILE CRACKING STRAIN AT THE COLLAPSE OF NUMERICAL ANALYSIS (outside view of east façade):
Numerical simulation

Unstrengthened building

- Shear crack in masonry walls

Strengthened building

- No more shear cracks
- Crack from the window corners

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Numerical simulation of the masonry building strengthened with 1 layer of SFRM

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Results of the finite element analyses

Damage pattern after the experimental test

Numerical crack pattern of the unstrengthened specimen

Numerical crack pattern of the specimen strengthened with 1 layer of SFRM

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Thank you for your kind attention!

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