FRCM - Strengthening of masonry vaults: the “Duomo di Colorno” and “Braidense Library” cases in Italy

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Abstract. In the last decade a re-discovering of the construction techniques and materials belonging to ancient buildings and heritage has grown up. Professionals and researchers have made a strong effort to understand resisting mechanisms in masonry buildings, trying to evaluate the safety factor in presence of vertical and horizontal seismic loads. As a consequence, innovative techniques and materials, as the FRCM, have been introduced to prevent local and global collapse mechanism, increasing the safety of the overall structure. The special cases of “Duomo of Colomo” and the “Braidense Library”, in Italy, are here presented. The XVIII century masonry vaults of the Duomo widely suffered due to a seismic event occurred in 2012 and a relevant crack pattern appeared. A similar situation occurred for the barrel vault of the Braidense Library due to settlement of foundations. In both cases, in order to restore the global resistance of the building, some consolidation interventions have been proposed and numerically evaluated. One of those is represented by a FRCM net applied on the upper side of the vaults. The system makes use of a carbon bi-directional fiber net inserted in an inorganic pozzolanic matrix, fully compatible with the ancient masonry support. Furthermore, besides this passive fiber intervention, an innovative active technique called “RAM – Reinforced Arch Method” was applied on the vaults of the Duomo. The use of post-tensioned steel cables, added to the FRCM net, led to a strong increase of the horizontal collapse load. Carbon fibers are able to induce a strong increase in the resistance of the masonry under the tensile stresses caused by seismic loads, avoiding the formation of cracks or plastic hinges. Several tests have been performed on FRCM, according to Standards. Some experimental results are here proposed.

Introduction

Nowadays there is no unanimous reply to the question “how a restoration has to be carried out?”. It is therefore necessary to define what the term “restoration” means and which are the principles that should be followed during a restoration intervention.

The international documents – the various “restoration charters” – offer a useful, but not exhaustive though. In fact, the principles they set out demand reasoned adoptions, rather than a scholastic act of faith. Anyway, there is one aspect that may be considered common to all restoration projects: in-depth analysis of the constituent materials and the structural condition of the monument under discussion.

The crucial value of reference in a consolidation intervention consists in safeguarding the ancient memory as the best foundation for the future, providing the necessary resistance to the structure. It follows that the conservation of heritages must be planned and executed on the basis of a deep analysis of the buildings, using materials and techniques that are mainly compatible with the existing ones and adopting the well known criterion of “minimum intervention”.

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The use of innovative materials and technique for strengthening ancient buildings has become a quite common practice among professionals in these last years. Anyway, every choice must be specific and well calibrated, remembering that each monument is irreplaceable and unique.

Hereafter two examples of strengthening of ancient masonry vaults by means of the FRCM - Fiber Reinforced Cementitious Matrix- Ruredil X Mesh C10 are presented. The first case deals with the “Duomo of Colorno”, while the second ones deals with the “Braidense Library – room of the manuscript” in Milan. In both cases, the detailed knowledge of the structure in terms of geometry, materials and loads has allowed to design a reinforcing intervention respectful of the authenticity of the places that were seriously damaged.

The study case of Duomo di Colorno

The XVIII century masonry vaults of Duomo di Colorno (Italy) strongly suffered due to a seismic event occurred in 2012 and a relevant crack pattern appeared.

In order to evaluate the global behavior of the church and the situation in terms of stresses in the masonry, an accurate Finite Element Model of the entire building has been realized, and a non-linear seismic analysis has been performed. A preliminary calibration of the parameters of the masonry in the model has been developed, mainly based on the comparison between experimental results, obtained during the flat-jack and dynamic tests, and the numerical ones.

Table 1: Comparison between experimental and numerical frequencies

<table>
<thead>
<tr>
<th>FREQUENCY [Hz]</th>
<th>Experimental</th>
<th>Numerical</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell tower</td>
<td>2.5</td>
<td>2.9</td>
<td>+15%</td>
</tr>
<tr>
<td>Church</td>
<td>6.0</td>
<td>6.011</td>
<td>+0.1%</td>
</tr>
<tr>
<td>Vaults</td>
<td>4.6</td>
<td>4.503</td>
<td>-2.1%</td>
</tr>
</tbody>
</table>

In table 1 the main numerical and experimental frequencies are reported. Concerning the experimental frequencies, three accelerometers have been placed on the bell tower, on the vaults and on the masonry of the church in order to get the H/V (Horizontal /Vertical) spectrum and to record the proper modes of the structures. Among all the modes introduced in the FEM numerical analysis, the only ones mainly involving the bell tower, the vaults and the church have been highlighted and compared with experimental ones. Differences are more than acceptable.

Furthermore, a simplified cinematic analysis concerning 28 collapse mechanisms has been applied to determine the multiplier of collapse load [7].

For both the numerical methods, results have shown that the non-strengthened structure was able to resist only to an acceleration of 1.6 m/s². At this value, that is significantly lower than the one really occurred in 2012, the cracks have opened in the vaults.
In order to restore the global resistance of the building, and to strength the 8 cm thick masonry vaults, some consolidation interventions have been proposed. First, a reinforcement of the vaults by applying a FRCM net – Ruredil X Mesh C10 has been adopted. The bi-directional fibers, positioned either on the extrados and on the intrados, at least for the most heavily damaged portions, has induced a strong increase in the resistance of the masonry under the tensile stresses caused by seismic loads, avoiding the formation of cracks or plastic hinges.

In the numerical analysis the FRCM reinforcement has been modeled through bi-dimensional shells elements, having the same mechanical and geometrical properties of the real material. It has demonstrated that, after the consolidation with FRCM, the first crack in the vaults appears for an acceleration of 2.0 m/s², higher than 1.6 m/s² corresponding to the situation before the structural intervention. This means that an increment of strength of about 25% in the horizontal acceleration has been reached.

In order to have a deep knowledge of the interaction between the FRCM and the ancient masonry, some “in-situ” tests have been performed on the vaults. They have provided more than satisfactory results in terms of bonding and tensile resistance of the X-Mesh C10.

**Table 2: Experimental results of the FRCM obtained during the test**

<table>
<thead>
<tr>
<th>Test no</th>
<th>Failure mode</th>
<th>Pull-off Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>Split on the external part of the mortar</td>
<td>2057 [N]</td>
</tr>
<tr>
<td>Test 2</td>
<td>Cohesion failure</td>
<td>790 [N]</td>
</tr>
<tr>
<td>Test 3</td>
<td>Adhesion failure</td>
<td>810 [N]</td>
</tr>
<tr>
<td>Test 4</td>
<td>Cohesion failure</td>
<td>680 [N]</td>
</tr>
</tbody>
</table>
Besides this passive fiber intervention, an innovative active technique called “RAM – Reinforced Arch Method” has been applied to strength the vaults. This technique consists in positioning post-tensioned steel cables on the extrados of the vaults, inducing a positive confining effect on the masonry, centering the curve of pressure. In the numerical model, post tensioned steel cables have been introduced by mono-dimensional beams elements, properly connected to the masonry vaults.

The combination of FRCM net and RAM on the vaults has induced an increment of the horizontal collapse load up to 69%, getting the formation of the first plastic hinges for 2.7 m/s². This value is close to 3.2 m/s², that corresponds to the design peak acceleration according to Italian Standards, so that the structure can be considered seismically improved.

Fig. 4 – The “Reinforced Arch Method” and FRCM on the vaults of Duomo di Colorno

Fig. 5 - Numerical results of the seismic analysis of the vaults (plan view). The non consolidated situation shows some cracks for an acceleration of 2.7 m/s² (top); no cracks appear after the strengthening with FRCM + RAM for the same acceleration (bottom)
The study case of Braidense Library in Milan

Another interesting intervention has been realized on the barrel vault of “Braidense Library – room of the manuscript”.

The ancient and frescoed vault, dated 1770, suffered a quite diffused crack pattern due to some excavations in the nearby of the building.

A Finite Element Model has been implemented to evaluate the state of stress in the masonry, applying several vertical displacement of the foundation, and comparing the numerical crack pattern with the real one.

A 50 mm vertical settlement of the foundation has been identified as the main cause of the cracks opening, and high values of tensile stresses in the masonry has been numerically detected.

Fig. 6 – Section and cracks detected on the vault of the Braidense Library before the intervention

Therefore, the strengthening of the barrel vault by applying Ruredil X-Mesh C10 on the extrados has been adopted. Among the advantages, we can mention the increase of tensile resistance of the masonry and the breathability to the steam that preserve the fine painted surfaces on the extrados.

The increase of resistance has been experimentally evaluated by applying indirect tensile stresses on several specimens, comparing three different configurations. Test 1 consists in one layer of FRCM applied on one side of the wall; test 2 consists in two layers of FRCM applied on one sides of the wall; in test 3 the layers of FRCM are applied on both sides. Results are reported in Table 3.

Fig. 7 – Breathability results and laboratory test device for FRCM – Ruredil
Table 3 – Test results: tensile strength on specimens

<table>
<thead>
<tr>
<th>Reinforcing type</th>
<th>$P_{\text{max}}$ [N] (avg)</th>
<th>$f_t$ [N/mm²] (avg)</th>
<th>$\tau_k$ [N/mm²] (avg)</th>
<th>$\tau_{ko}/\tau_{ki}$ (avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-reinforced</td>
<td>$35 \times 10^5$</td>
<td>0.37</td>
<td>0.33</td>
<td>1</td>
</tr>
<tr>
<td>One side – single layer</td>
<td>$54.15 \times 10^5$</td>
<td>0.57</td>
<td>0.51</td>
<td>1.55</td>
</tr>
<tr>
<td>One side – double layer</td>
<td>$94.2 \times 10^3$</td>
<td>0.99</td>
<td>0.90</td>
<td>2.69</td>
</tr>
<tr>
<td>Two side – double layer</td>
<td>$122.9 \times 10^7$</td>
<td>1.29</td>
<td>1.18</td>
<td>3.51</td>
</tr>
</tbody>
</table>

Materials and Technologies: the use of FRCM

In the applications described in this paper a new structural reinforcement FRCM - Fiber Reinforced Cementitious Matrix has been proposed instead of traditional FRP – Fiber Reinforced Polymer.

The use of FRCM has several advantages respect to the use of FRP. In fact, the main drawbacks of the FRP are the low durability of epoxy resin and the low resistance of high temperature, despite the excellent mechanical performances of a synthetic or mineral fiber.

First, the epoxy resin of FRP is characterized by a critical temperature (known as “glass transition temperature ($t_g$)”) of 30-60°C, in presence of high humidity (more than 60%). Under these conditions, the resin changes its physical state from rigid to amorphous and mechanical properties strongly reduce. This fact doesn’t happen for the pozzolanic hydraulic binder of FRCM.

Second, according to fire standard “UNI EN 13501 - Part 1”, FRP is classified as class E (flammable material), while FRCM are classified as A (no flammable). As a consequence, FRP has to be protected from fire with the application of special calcium-silicate panel, at least 7 cm thick, while FRCM maintains its mechanical properties unchanged up to a temperature of 550 °C.

Durability, reliability, compatibility with masonry support and breathability of the C-FRCM system (Ruredil X Mesh C10) have been subjected to laboratory tests.

In the following, the main results of the tests are reported, according to the Reference Standard [8].

The test objective was to determine the tensile strength, elongation, modulus of elasticity and lap-tensile strength of the FRCM strengthening composite system, using specimens under ambient conditions.

Hereafter the test set-up is summarized:

- **Specimen Size**: Nominal single ply FRCM, rectangular coupon size 410 x 51 x 10 mm length x width x thickness, respectively.

- **Specimen Layout**: Coupons were cut from larger FRCM material panels with a nominal size of 410 x 560 mm length x width, respectively. Fiber alignment was set in the 0° direction along the length of the coupon for C-FRCM (Ruredil X Mesh C10).

Lap Tensile Strength coupon specimens were made following the same methodology, with the difference of a nominal mesh overlap length of 120 mm.

- **Load application and measurement**: Uniaxial tensile load was applied to all specimens. Axial deformation was measured using a clip on extensometer. Coupons were gripped with a clevis type, chosen to maximize degrees of freedom and reduce any bending.

Fig. 7 – Test setup with specimen coupon
Results show that the stress-strain behavior of C-FRCM control coupon specimens is bi-linear as expected. The initial branch of the curve corresponds to the un-cracked specimen, followed by a second branch with a reduced slope, corresponding to the crack specimen.

The primary failure mode of the C-FRCM coupon specimens was slippage of the fibers after multiple cracking throughout the length of the specimen, perpendicular to the direction of the load; then, secondary de-bonding failure mode located at the tab ends was observed in some cases.

Some other tests were performed on the C-FRCM, changing the ambient exposure. The test objective was to determine the environmental resistance of the composite system by evaluating the residual tensile and lap-tensile strength, after freeze and thaw cycles and aging.

Hereafter the test procedures are reported:

- **Freeze/Thaw Environment**: Specimens were conditioned for one week in a humidity chamber at 100% RH at a temperature of 37.7°C. Subsequently, specimens were subjected to 20 freeze-thaw cycles. Each cycle consisted of a minimum of 4 hours at -18°C followed by 12 hours in the humidity chamber (100% RH and 37.7°C).

- **Aging**: Specimens were exposed independently to three types of environmental aging conditions as referred to in Table 2 of [8]. The first specimens were introduced in a humidity chamber at 100% RH and 37.7°C. The second specimens were fully submerged in saltwater at laboratory conditions. The third specimens were submerged in an alkali environment, a solution consisting of calcium hydroxide (Ca(OH)₂), sodium hydroxide (NaOH), and potassium hydroxide (KOH) mixed to create an environment at a pH > 9.5.

As results, the C-FRCM tested were able to pass the acceptance requirements provided in Sections 4.2.3 and 4.7 of [8]. In particular, the following characteristics post-conditioning were verified, and in most of the tests even over-passed:

- Freezing and Thawing: coupons specimens retained at least 85% of the tensile strength properties.

- Aging: coupons retained at least 85% of the tensile properties after 1000 hours of exposure, and at least 80% of the tensile properties after 3000 hours of exposure.

In Fig. 9 the results of the tests conducted on C-FRCM are shown. The average reference strength according to [8] (tensile Control bar, in balck) of 800 MPa was over-passed by all the 14 specimens of C-FRCM Ruredil tested.

Furthermore, the primary failure mode of the C-FRCM coupon specimens was slippage of the fibers after multiple cracking, throughout the length of the specimen, perpendicular to the direction of the load, similar to the control specimen.
Conclusion

The use of FRCM in consolidation interventions of ancient buildings and heritages has grown up in the last decades. The increases of strength and ductility of masonry structures represent some of the advantages of the Ruredil X Mesh C10.

FRCM allows to satisfy the requirements of the Italian and International Standards in terms of seismic behavior, conferring a seismic improvement, or even a seismic adjustment, to the overall structure. Beside this, compatibility, breathability, resistance to freeze and thaw cycles and resistance to environmental exposure are some of the technological characteristics of X Mesh C10.

Furthermore, to study in deep the behavior of X Mesh C10 related to ancient masonry structures, a large scale experimental campaign is being conducted by the authors, evaluating global and local response of FRCM application itself (passive system) and FRCM + Reinforced Arch Method (active system).

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