Strengthening of masonry structures with Fibre Reinforced Plastics: From modern conception to historical building preservation

M.R. Valluzzi

DAUR, University of Padua, Italy

ABSTRACT: Modern techniques and innovative materials are often rapidly proposed and allowed in the current practice, even for restoration of historical constructions, where fundamental preservation criteria have to be taken into account. The large variability and complexity of masonry structures and typologies make particularly difficult the preliminary choices for proper structural models and interventions, that should be based of suitable knowledge of both existing and new materials, and of their interaction under environmental and loading conditions. Despite the increasing number of specific studies of FRP reinforcement on masonry structures, still limited codes and recommendations are available so far. Harmonization of test procedures and methods should be pursued, in order to compare results and calibrate analytical and numerical models for design and assessment rules.

1 INTRODUCTION

In the last two decades, among modern and innovative solutions of intervention on existing structures, composite materials, as FRP (Fiber-Reinforced Plastics), have been increasingly considered for strengthening and repair of both modern and historic masonry constructions (buildings, bridges, towers) and structural components (walls, arches and vaults, piers and columns).

FRP material systems are composed of fibers embedded in a polymeric matrix, which bind and protect the fibers themselves, in order to allow load transferring and to activate their mechanical properties. High tensile strength and stiffness-to-weight ratio, fatigue and corrosion resistance, easy in-situ feasibility and adaptability, and progressive reduction in production and distribution costs, are the main characteristics that encouraged the diffusion of these materials at different levels: to improve the global behaviour in seismic zone (tying, connections among components, strengthening), to counteract specific incipient or developed damage (high compression, shear and/or flexural conditions), and to repair very specific local weaknesses depending on the peculiar construction typology. No yielding is exhibited prior fibres failure, and sensitivities to impact, notching and environmental agents could be present. Fibres activate their characteristics along their prevalent distribution, whereas have negligible properties in the other directions.

Despite the large accessibility to various products (bars, strips, laminates, sheets, cords, grids), made of several reinforcing materials (carbon, glass, aramid, ... ) and applicable in different modalities on masonry structures (embedded inside grooves or bed mortar joints, externally bonded or anchored), design rules for the interventions, feasibility recommendations and procedures aimed at checking the effectiveness of the technique and monitoring are still under definition.

Starting from extension of approaches proposed for concrete structures, and after the critical evaluation of the impact of generalized interventions on historical structures (Giuffre 1993, Tomazevic 1999, Binda et al. 2006), researches and studies have been more and more focused on the specific features of the masonry material, by recognizing its lack of homogeneity and the large variability of typologies and constituent basic materials and aggregations (brick, stones, mortar, mixed arrangements, ...).

This approach has led to a new impulse for the upgrading of standards devoted to masonry in seismic zone, which often include reference to specific codes or recommendations on the possible application of FRPs, unfortunately still very limited (e.g. the OPCM 3431/2005 and CNR-DT 200/2004, in Italy; ACI 440M/2004 in US).

The adoption of FRPs for strengthening is mainly aimed at reinforcing masonry structures and components by increasing their ultimate capacity (strength and displacement), and often this is achieved by
modification of mechanisms at collapse, which can involve further resisting phenomena.

What essentially emerges from the analysis of a number of works available in literature aimed at investigating the mechanical performances of strengthened structures and components, and from the code proposals, are still needs of:

– definition and putting into practice specific cautious criteria for possible application of composite materials in the historical construction preservation field;
– clarification of critical aspects of application technologies (e.g., bond and anchorage of textiles and bars);
– standardization of methods and experimental procedures for the characterization of the mechanical performance of strengthened components to define proper design and assessment criteria;
– definition and validation of investigation procedures for the evaluation of the effectiveness and durability of the intervention.

2 MATERIALS AND COMPONENTS

2.1 Strengthening materials

Among different solutions addressed to masonry structures, FRPs are usually proposed as application of near surface mounted bars (cylindrical or prismatic reinforcement inserted in grooves cut on the masonry surface) or structural repointing (bed joints reinforcement) (Nanni et al. 2003), and externally bonded sheets or laminates (wet lay-up system) (Figure 1).

The use of Carbon and Glass fibres is predominant in comparison with other types, due to their higher accessibility on the market and of sufficiently high mechanical properties (usually compared with ordinary steel), together with epoxy resins for external gluing, and/or modified mortars for embedment in joints or grooves.

More recently, various inorganic products (cement, lime or clay grout) are introduced as support for fibres, in order to combine more suitable materials for the intervention on different components of existing structures.

Textiles and sheets present the high advantage of flexibility, allowing disjointed portions or even whole structures to be wrapped; nevertheless, a proper preparation of the surface of application is needed (sandblasting, laying of primer and putty), and aesthetics reestablishment should taken into account. The bond at the masonry-FRP interface is the main responsible for the mechanical performance of the intervention and of the strengthened component.

On the contrary, application of bars do not require particular preparation works of component surface in comparison with laminates but, due to the brittleness to folding, specific solution for anchorage should be adopted (Figure 2). Small diameter bars or strips are used in the bed joints and a special care should be taken in the repointing phase, in order to incorporate the new reinforcing system in the behaviour of the masonry. The aesthetics of the surface is commonly preserved in this case.

2.2 Masonry typologies and damage

Existing masonry constructions could be part of modern constructive systems or historical contexts (Figure 3). Their behaviour and proneness to damage are connected to specific hazardous conditions (e.g., seismicity, subsidence, high lateral or vertical loads), which consequently influence the choice of intervention solution.

Therefore, classification of masonry and damage is fundamental, as it could be even very peculiar and diversified among countries, depending on specific constructive and typologies history (Modena 1997, Binda et al. 2006).

Materials may be very different (solid or multi-leaf sections), as well as their combination in structural systems (load bearing or infill walls, vaults and columns).

In this context, FRP reinforcement could have potential in (Figure 4):

– counteracting global or partial overturning (façades or corners of buildings) and improve collaboration among components;
– in-plane or out-of-plane strengthening (walls under shear and bending);
3 TEST METHODS AND ANALYSIS

3.1 Experimental procedures


Harmonization of experimental procedures is a urgent need that international bodies of standardization and related professional corporations should considered, in order to allow comparison among results.
Figure 6. Experimental tests on local mechanisms: pull-off tests on surface (a), brick-FRP adhesion test (b), adhesion on mortar joints (c), splitting of rods (d).

Especially for aspects non easy to clarify as the effective contribution of the reinforcement on shear and combined actions, as well as the influence of delamination in reducing the efficiency of the bond at the interface, homogeneous methods should also be set to allow proper calibration of analytical and numerical models.

3.2 Standards and recommendation proposals

Despite the several documents available as codes or guidelines for application of FRP in concrete structures, at present only the CNR-DT 200/2004 and the drafts of ACI 440 are available.

In both cases, the formulations proposed for reinforced masonry, derived from of the theoretical approach of reinforced concrete, is mainly adopted. Bond and shear are definitely the main problematic aspect to clarify, as standard experimental methods are not provided, and analytical models are often not in agreement among them.

As an example, the well-known truss analogy is considered for the analytical formulation of shear behaviour, particularly suitable for infill walls, where the corner crushing limit is preferred to diagonal cracking or sliding shear. The contribution of FRP ($V_{m,f}$ or $V_{Rd,f}$) is added to the strength of plain masonry ($V_m$ or $V_{Rd,m}$) as follows. For ACI 440:

$$V_m = 4.0 - 1.75 \left( \frac{M}{Vd} \right) A_s \sqrt{f_m} + \frac{P}{4}$$

where $M$ is the maximum moment at the section under consideration, $V$ is the corresponding shear force, $d$ the distance from the extreme compression fibre to the centroid of tension reinforcement, $f_m'$ is the compressive strength of masonry, $A_s$ is the compressed area of masonry, $A_f$ is the reinforcement area, $P$ is the axial load, $f_{fc}$ is the design strength of FRP, and $s$ in the spacing of horizontal reinforcement in the vertical direction. For CNR DT/200, the analogy with the design formulas proposed for reinforced masonry beam, as in the Eurocode 6, is evident:

$$V_{Rd,m} = \frac{1}{\gamma_{Rd}} df_{cd}, \quad f_{cd} = \frac{f_{cd}}{\gamma_{cd}}$$

where $t$ is the thickness of the wall, $f_{cd}$ is the design shear strength of the wall by using a Coulomb friction law, $A_{fs}$ is the area of reinforcement parallel to the shear action, $f_f$ and $\alpha$ are the spacing and the inclination of the reinforcement, $f_{fs}$ is the strength of the reinforcement, assumed as minimum between the design tensile strength and the delamination load, $\gamma_{fs}$ (equal to 1.2 in this case) is the partial safety factors for design, whereas partial factors applied on materials are $\gamma_{M}$ and $\gamma_{f}$, for masonry and FRP respectively.

Actually, in-plane rotation, and compression combined with other conditions could affect the strengthened component subjected to lateral actions, and proper limitation of the effectiveness of the intervention due to lack of bonding and or environmental conditions should be taken into account (Figure 7). In this connection, the two documents still present several dissimilarity in the definition of reducing factors of the nominal tensile strength and the rupture strain of FRP for creep and environmental exposure, as evidenced in (Garbin et al. 2006), ranging from 0.80 to 0.30 for the Italian standard and from 0.55 to 0.20 for the US one, respectively for Carbon or Glass FRP. Moreover, proper coefficient (namely $k_{m}$ and $k_{f}$) should be considered to take into account debonding influence in flexural and shear capacity, depending on several factors, as: the strengthening systems and configurations, the materials at the interface, the amount and distribution of FRP, etc. On the basis of experimental results these coefficient can vary from 0.2 to 0.8, being particularly low under shear conditions (Garbin et al. 2006).

By considering the results available in literature obtained by diagonal compression tests, an integration of these data is possible. Actually, diagonal compression led to different failure mode (usually splitting),
Figure 7. Debonding of CFRP strips due to peeling (a), FRP rupture beyond bonding limit (b).

Table 1. Diagonal compression tests.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Unit type</th>
<th>Disposition</th>
<th>Sides</th>
<th>n. Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valluzzi 2002</td>
<td>Clay</td>
<td>Diagonal</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Yu 2004</td>
<td>Clay</td>
<td>Horizontal</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Yu 2004</td>
<td>Clay</td>
<td>Vertical</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Grando 2003</td>
<td>Clay</td>
<td>Horizontal</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Valluzzi 2002</td>
<td>Clay</td>
<td>Net</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Valluzzi 2002</td>
<td>Clay</td>
<td>Diagonal</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Gabor 2006</td>
<td>Clay</td>
<td>Diagonal</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Yu et al. 2004</td>
<td>Clay</td>
<td>Horizontal</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Yu et al. 2004</td>
<td>Clay</td>
<td>Vertical</td>
<td>1</td>
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</tr>
<tr>
<td>Grando 2003</td>
<td>Clay</td>
<td>Horizontal</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tinazzi 2003</td>
<td>Clay</td>
<td>Vertical</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Valluzzi 2002</td>
<td>Clay</td>
<td>Net</td>
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<td>7</td>
</tr>
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<td>Tinazzi 2003</td>
<td>Clay</td>
<td>Net</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Yu 2004</td>
<td>Concrete</td>
<td>Horizontal</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Yu 2004</td>
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<td>Vertical</td>
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<td>Yu 2004</td>
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<td>Yu 2004</td>
<td>Concrete</td>
<td>Vertical</td>
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<td>1</td>
</tr>
<tr>
<td>Grando 2003</td>
<td>Concrete</td>
<td>Horizontal</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Morbin 2003</td>
<td>Concrete</td>
<td>Horizontal</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

than modes involving friction (as for the application of the Coulomb law, adopted in the formulation proposed by standards), but it is still widely considered on experimental basis, due to its particularly easy execution. More reliable combined vertical and lateral load setup are progressively adopted for shear, but available results on literature are still very limited. Uniformity for diagonal compression test should at least concern the dimensions of the walls, to be not lower than 1 m for side, in order to avoid local effects in small size elements.

The samples given in Table 1, available from application of mainly CFRP and GFRP sheets by wet lay-up system, are rather comparable among them, even deriving from different reinforcement configurations and type of support.

By taking into account a reference mean value for the strength of unreinforced panel of about 100 kN and 140 kN for clay and concrete walls, respectively, the increase of strength grouped by configurations is depicted in Figure 8. The best performances, due to diagonal and symmetrical dispositions, are confirmed. The improvement in shear strength is comparable between clay and concrete masonry, and the highest values are mainly related to GFRP.

By analyzing the data in comparison with the normalized maximum strength of the reinforcement \( \omega \), given by the ratio of the maximum FRP tensile strength \( (E_f/A_f) \varepsilon_f \) and the reference value of the shear strength of masonry \( \tau_m \), computed on the net diagonal area, multiplied by the gross area of the panel \( A_m \), results are as in Figure 9.

Double values of the strength are obtained in a rather large range of maximum strength of the reinforcement.

By defining an efficiency factor \( k_v \), as ratio between the increase of load measured by the diagonal test and the maximum normalized FRP strength, the highest effectiveness is achieved by minimum amount of reinforcement by using the diagonal symmetrical pattern (0.65–0.85 on clay bricks, halved in the case of single side applications); unidirectional pattern (usually in the horizontal direction) shows a good behaviour, equivalent or even better if compared with grid patterns, even if symmetrical (Figure 10).

Also for bonding, the reference models are adopted from the concrete approach; many strength models have been developed in the last decade, but, again, the lack of standardization of harmonized procedures
Figure 10. Effectiveness factor for shear strength for different amount and configuration of FRP reinforcement.

for experimental tests, led to results often difficult to compare. CNR DT/200 adopts as bond length $l_c$ and strength $f_{fild}$ the following formulations:

$$l_c = \frac{E_f \cdot t_f}{\sqrt{f_{fml}}} \quad \text{(mm)}$$

$$f_{fild} = \frac{1}{\gamma_M \cdot \gamma_{f,D}} \cdot \frac{E_f \cdot t_f}{t_f} \cdot \sqrt{f_{fml}}$$

(5)

where $\gamma_M = c_1 \cdot \sqrt{f_{fml}}$ (N mm) is the characteristic value of the fracture energy, $E_f$ is the Young modulus of FRP in the direction of the applied force, $t_f$ is the FRP thickness, $f_{fml} = 0.1f_{mk}$ is the mean tensile strength of masonry (considered coincident with the strength of the blocks), $\gamma_M$ and $\gamma_{f,D}$ are partial safety factors, varying from 1.1–1.25 and 1.2–1.5, respectively, depending on the certification of the entire bonding system on the support, or of only the single materials. $c_1$ is a coefficient to identify on experimental basis or to adopt equal to 0.015 (0.03 is proposed for concrete with the same equation).

The non homogeneity of masonry due to the presence of mortar joints, and the consequent influence in the bonding phenomenon of the different mechanical properties and of the geometrical discontinuity, are not considered in the model; moreover, a unique significant value for the fracture energy along the connection is assumed.

A fundamental contribution to clarify these aspect is done by several research groups (Briccoli Bati et al. 2001, Aiello et al. 2003 and 2006, Casareto et al. 2003, Basilio et al. 2005, Panizza et al. 2008), but different test procedures are adopted, thus comparison of results is often unreliable. In particular, the most suitable arrangements could be the double-lap (DL) (Figure 11) and the single-lap shear test (SL), the latter being the most effective, due to the problem of reproducing actual symmetry of load distribution in the DL configuration, but not simple to realize, in comparison with the former one.

The identification of $f_{fild}$ is crucial, as it represents the parameter strictly related to the efficiency of the connection between reinforcement and masonry. The comparison with the application of equations (5) and the elaboration of experimental data able to define efficiency laws for debonding as in (Panizza et al. 2008), allowed to calibrate a FE model (with DIANA), in order to simulate the performance of shear and flexural strengthening with CFRP sheets applied in a masonry wall including openings. The scheme of the model is depicted in Figure 12, and the comparison among the main parameters at the interface between reinforcement and masonry, to be used for the model, are given in Table 2. Experimental elaboration obtained by DL shear tests have been considered, taking into account a reduction of 30% to obtain reasonable characteristic values, to compare to the ones computed according to the CNR standard.

The main characteristics of materials were derived from available experimental tests, or computed on the basis of the national standards. For clay bricks, a characteristic compressive strength of 41.2 MPa, a mean tensile strength of 2.4 MPa and an elastic modulus of 16 GPa, were assumed; a mortar M2.5 (MPa, compression) was considered, whereas computed global
Table 2. Mechanical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific fracture energy $\Gamma_f$ (N/mm)</th>
<th>FRP maximum strength (delamination) $f_{\text{frd}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNR DT 200</td>
<td>0.04</td>
<td>335</td>
</tr>
<tr>
<td>DL shear tests</td>
<td>0.99</td>
<td>1660</td>
</tr>
</tbody>
</table>

Properties of masonry were: 8.5 MPa for the compressive strength, 8500 MPa and 3400 GPa for the elastic and the shear moduli, respectively, and a Coulomb law for shear strength calibrated with parameters equal to 0.3 as cohesion and 0.4 as friction coefficient. High-strength CFRP applied in strips 100 mm wide were considered, having nominal elastic modulus of 230 GPa and equivalent thickness of 0.165 mm. Loads derived from a three storey building were assumed, and the simulation of the effect on the base floor was performed.

From Table 2, the maximum fracture energy and the limit of experimental delamination are thus about 25 and 5 times higher than the valued proposed by the code, respectively. Four configurations were considered, characterized by progressive reinforcement, from plain masonry to global horizontal confinement, up to application of horizontal and vertical strips on the main walls, 50 cm spaced (Figure 12). Non-linear push-out analysis were performed, by considering progressive increase of horizontal acceleration, uniformly distributed along the height of the wall.

The numerical results are given in Figures 13 to 15. To take into account a possible residual bond after delamination occurrence, the comparison between the assumption of a elastic-brittle or elastic-plastic law for the FRP behaviour was considered.

Figure 13. Comparison among plain masonry and three strengthening configuration by using experimental elaborations and elastic-brittle law for FRP strips.

Despite the simplification adopted in the modelling, several points can be discussed, by analyzing the diagrams which compare the imposed acceleration to the displacement at the control point (Figure 12.a). First (Figure 13), by considering the experimental elaboration on fracture energy and delamination, the unreinforced model is subjected mainly to rocking, confirming the high vulnerability of masonry buildings to rigid movements (a). The shear strength is not activated in the walls, and the preliminary horizontal tying is not able to increase the peak load, but only to homogenize the plateau in the plastic branch (b). By introducing vertical strips, the load is significantly increased, with minor differences between flexural (c) and combined shear (d) reinforcement. The elasto-plastic behaviour of FRP is able to increase of about 25% the peak load in the complete strengthening configuration, and to guarantee a constant plastic plateau (Figure 14).

The comparison with models where fracture energy parameters are assumed as in the CNR standards revealed minor performances, thus confirming the proposed models being highly conservative (Figure 15). This is surely safety oriented, but if not controlled in its boundaries could induce overestimation of FRP design, and consequent utilization of unnecessary reinforcement. Moreover, the sensitivity of CNR assumptions to the elastic-plastic or elastic-brittle behaviour of FRP are less evident in comparison with experimental elaboration of basic parameters.

Finally, it is worth to remark that experimental results on bond are available by tests where FRP is glued only on brick surface, neglecting the significant influence of mortar joints in the complex adhesion phenomenon involving the masonry.

4 FEASIBILITY IN HISTORICAL BUILDINGS

4.1 Reference criteria

Interventions to perform in historical environment cannot disregard to satisfy the specific requirements on which preservation is based.
It is worth to remark that, even in very hazardous conditions, as mainly occur in seismic zone, a proper compromise has to be taken among safety and preservation, keeping priority the safeguard of human life. This enable to reduce and control upgrading, in favour of alternative measures of improvement, specifically targeted to the large complexity of historic masonry and constructions (ICOMOS/ISCARSAH). Recent updating national codes (e.g., OPCM 3431/2005 seismic code in Italy) finally provide specialized sections for existing masonry, recognizing the differences in typologies and materials, and by pointing out the great importance of preliminary knowledge, supported by the suitable application of in-situ non-destructive (ND) and minor-destructive (MD) tests.

Nevertheless, the Charter of Venice (1964), the Declaration of Amsterdam (1995) and the Charter of Krakow (2000), could be considered reference documents for the definition of criteria and actions devoted to Cultural Heritage. Minimum interventions, having characters of “reversibility” (intended as substitutability or removability); use of materials and techniques compatible with the original ones, able to guarantee durability to the intervention itself and, consequently, to the building; respect to the original functions (both structural and of utilization), distinguishability of the intervention; all these criteria should be considered when proposing repair or strengthening of historic structures.

FRP has a great potential to improve the brittle behaviour of masonry components, but many aspects related to its interaction with traditional materials and durability are still under experimental study, especially due to the use of resins as bonding system.

More recent studies are focused on the use of organic matrices, as FRCM (Fiber Reinforced Cementsitious Matrix) or TRM (Textiles Reinforced Mortar) (De Lorenzis et al. 2004, Prota et al. 2006, Papanicolau et al. 2007), and could represent significant steps for the identification of compatible binders with original masonry.

Cautious approach should dominate, as well as the basic principle that intervention now has not to pretend to be definitive, as further more appropriate measures can be more reliable in the future.

The CNR DT-200 itself declare that interventions with FRP on monuments and historical architecture have to be justified as indispensable for the building, and the respect of the above-mentioned principles of restoration has to be guaranteed.

4.2 Some cases study and applications

The current use of FRPs in restoration work, should be particularly cautious when dealing with historical constructions, as many restoration principles cannot be fully satisfied. On the contrary, their high mechanical performances can be usefully exploited, where other systems fails or are more invasive. Especially textiles and bars have the main advantage of not increase dimensions of strengthened sections, thus their use, if properly designed to solve specific problems, can be targeted to large elements, but also to solve very peculiar weaknesses, not only in standard bearing masonry constructions. Some examples are given in the following.

Even if in large assemblages, FRP can be very versatile to repair urgent local cracks, as part of combined
intervention. As an example, the consolidation of the very depressed thin vault of the central hall of Villa Bruni in Megliadino S. Vitale (Padova), has included the repair with FRP strips of the main cracks at the intrados and the extrados, together with other tying measures acted by the timber beams of the floor. FRP strips were designed and assessed by using a specific method applied to vaults, taking into account the modified failure mechanisms of the strengthened structure (Valluzzi et al. 2002 and 2004).

Other applications on vaults can be combined with injections, as well as ties, to improve the global behaviour, as in the church of S.ta Corona of Vicenza, where cross vaults have been reinforced at their extrados with strips 20 cm wide in their longitudinal direction (Figure 17).

In the church of S.ta Maria in Organo of Verona, the intervention with FRP has been limited to the in-plane reinforcement of the walls stabilizing the vaults from the sides and to existent transversal ribs, as well as new ones, provided in the longitudinal direction (Figure 18).

Finally, specific applications where the high versatility of FRP laminates can hardly even the performances of other materials, are the local repair of weaknesses in stone elements, being part of structures or monuments. As an example, the confining of capitals can be performed, to substitute or integrate actual metal rings, as executed at the top of the columns of the ‘Palazzo della Ragione’ in Padova. CFRP strips have been positioned after restoring of the capitals and successively hidden beneath the historical original metal confining elements (Figure 19). Another peculiar example is the reinforcement of the basement of a equestrian statue characterizing the marble monumental tomb of Cansignorio in Verona, particularly deteriorated by metal oxidation and environmental aggression. A system of superimposed layers of CFRP has allowed to rebuild the loose parts of the bearing elements, re-establishing the aesthetics of the statue (Gaudini et al. 2008).

Therefore, in monuments, where the aesthetics could be the most important requirement, the
intervention can be focused on a precise defect to repair, providing a proper covering of the surface (with marble chipping or similar) to hide the structural integration. Other materials, like steel, despite similar advantages from a structural point of view, cannot have the same versatility and possibility in applications, preserving aesthetics at the same time.

5 CONCLUSIONS

FRP materials have high potential for the improvement of mechanical performance of structures, also for masonry components, provided that preservation criteria are satisfied in the field of historical constructions.

Practical applications on historical masonry structures are mainly focused on the use of sheets, aimed at:

- confining structural components (columns, towers) or repairing specific damage of materials (statues, capitals, etc.) which can be protected by oxidation or other attacks;
- stabilization (as contribution, often together with other interventions) of curved structures (arches and vaults in buildings and bridges) and local repair of cracks.

Moreover, FRP can allow very light interventions, able to stabilize local critical conditions and/or to integrate original materials.

The impulse in their rather common use in the last decade, contributed to lower the costs for production and distribution, thus their availability on the market is more and more increasing. Nevertheless, many aspects still are under investigation, and specific experimental procedures and models need to be homogenized in standards and recommendations.

Therefore, from more and more modern conceptions, today more than in the past, we need to resume traditional values, in order to not forget our learning from history and to respect constructive specificity and functions of the original structures. Innovative solutions can be very useful even in the Cultural Heritage context, provided that we are able to recognize their limits, and to pursue the clarification of all aspects (both positive and negative) that are involved in the delicate question of the preservation of historical constructions.

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