Environmental durability of the bond between the CFRP composite materials and masonry structures

S. Briccoli Bati and T. Rotunno
University of Florence, Department of Constructions, Florence, Italy

ABSTRACT: In the consolidation of masonry structures, new technologies for reinforcing structural members are becoming ever more wide-spread. Such technologies consist of the application of overlays of carbon-fiber textiles embedded in a polymer matrix, called CFRP (Carbon Fiber Reinforced Polymers), which are similarly applied to the surface of masonry building elements.

Two main reasons motivate the use of CFRP materials in masonry restorations: ease of application and the material's intrinsic properties, such as its high mechanical strength per unit weight, resistance to chemical agents and electrical and magnetic neutrality.

However, to date, information is lacking on the durability of the bond between the masonry substrate and the CFRP composite, a bond that could very well depend on environmental conditions. This paper focuses precisely on the environmental resistance and durability of this interface.

Brickwork specimens, prepared with CFRP composite reinforcement made from commercially available components, were subjected to wet-dry as well as freeze-thaw cycling to simulate weathering. Exposure times were varied and the samples removed for shear tests up to failure.

The results of such tests are reported, and the load-bearing capacities of artificially weathered reinforced samples compared to those of both unreinforced controls and unweathered reference units.

1 INTRODUCTION

Following demonstrations of their efficacy in strengthening reinforced concrete structures, modern reinforcement techniques based on the application of strips of composite material based on CFRP (Carbon Fiber Reinforced Polymer) are finding ever-wider adoption in the field of masonry structures. In fact, apart from improving the mechanical performance of the structures to which they are applied, such reinforcing techniques offer other benefits, such as the low weight of the materials applied, the reversibility of the operations, and enhanced resistance to corrosive agents. Combined, these features have attracted ever-greater attention on the part of experts in the field and assured a promising future for the wide spread adoption of CFRP reinforcing systems.

In recent years, the number of rehabilitation operations based on the application of these techniques has grown considerably, especially in Italy, where to a number of seismic events have devastated historical city centers with a preponderance of masonry buildings,.

FRP composite materials consist of strong fibers, such as carbon or glass, embedded in a matrix, which may be vinylester, polyester or epoxy resin. In such composites, the fibers provide the strength and stiffness, and the matrix furnishes the capacity to transfer loads amongst the fibers.

These materials are highly anisotropic because of the lengthwise arrangement of the long-fiber reinforcements and are applied to masonry structural elements to compensate for such elements' low tensile resistance.

Although some research has already been conducted to determine the durability of these new techniques, most studies have focused on the resistance of the composite material alone. Little data is available regarding the effectiveness over time of the overall structural unit represented by the masonry support consolidated with fiber-reinforced composite, or their susceptibility to the degrading effects of atmospheric agents.

Given the growing adoption and acceptance of CFRP reinforcement operations on historical masonry structures, it seems that careful consideration of their true effectiveness is called for, as are empirical evaluations, not only of their mechanical performance, but also of the durability of the bond between the substrate and the fiber-reinforced composite.

The goal of the present work is to investigate the effectiveness of the adhesion between composite materials and masonry when the structural system, in its entirety, is subjected to attack by environmental agents. To this end, we studied CFRP-reinforced brick masonry specimens subjected to degradation in the laboratory through various different types of artificial weathering designed to simulate the actions of environmental agents.

2 ENVIRONMENTAL DURABILITY STUDY

2.1 Testing program

Experimental trials were conducted using 84 expressly-fashioned masonry specimens, made of brickwork with bastard mortar. With the purpose of obtaining a basis for comparison in order to evaluate the effectiveness of the reinforcement, 78 of the total were reinforced with CFRP strips and 6 subjected to testing without reinforcement.

The specimens were subjected to alternating cycles of wet-dry and freeze-thaw. Periodically, a set of six specimens was withdrawn from the treatment chamber and subjected to mechanical testing to determine the breaking load and thereby evaluate, on the basis of the ultimate load values recorded, the degree of degradation of the adhesion between the brick masonry substrate and the CFRP composite strip induced by the artificial weathering.

2.2 Test Specimens

Each 16.6×12×30 cm specimen was made up of three bricks bonded along three fourths of their major surfaces through bastard mortar joints (fig.1). After the 28 days necessary to guarantee good curing of the mortar, the CFRP reinforcement was applied to two faces of the specimen (fig.2).

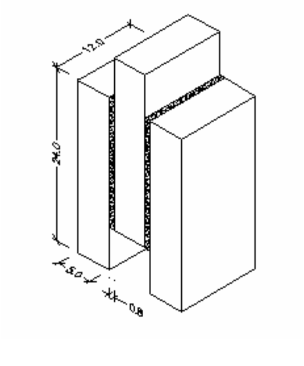

Figure 1: Unreinforced specimen

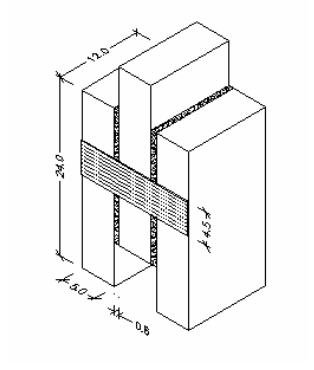

Figure 2: Reinforced specimen

The 4.5 cm-wide CFRP strips were applied in lengths of 16.6 cm to the two sides bearing the mortar joints (i.e., across the entire three-brick width of the specimen).

The specimens were subjected to loading conditions for which the only possible mechanism of failure was represented by separation of the composite from the brick masonry support. The peak load values were then used to evaluate any weathering cycle-induced degradation suffered by the specimens at the interface in correspondence to the contact surfaces.

The CFRP reinforcement material used is a commercially available fibrous composite with a polymer matrix. For the tests, it was applied by meticulously following the manufacturer's instructions:

- initial cleansing of the surfaces destined for application of the reinforcement layer;
- coating with a two-component primer (low viscosity), which enhances adherence of the reinforcement to the support;
- application of a first layer of matrix, composed of a two-component epoxy paste;
- insertion of the carbon-fiber fabric through application with a spatula to avoid gaps;
- and lastly, application of a further layer of epoxy resin.

All specimens were left at room temperature for at least 7 days before testing and before being subjected to the environmental tests.

2.3 Test Methods

The treatments were designed with the aim of simulating weathering by atmospheric agents that normally act on a masonry building: cycles of alternating wet-dry and freeze-thaw. The thermal excursion for the freeze-thaw cycles was determined by considering the climatic conditions characteristic of the countryside in the central Italian region of Umbria, where the most recent earthquakes have struck.

Three different programs of artificial weathering were performed: the first two called for subjecting the specimens to wet-dry cycles, and the third one to alternating freeze-thaw.

Program 1 (wet-dry) was performed on 24 specimens, 6 at a time, in four different sets. Each single cycle consisted of full immersion of the specimens in water for 10 minutes followed by air drying for 48 hours. The four different sets of six specimens were subjected to a different number of wet-dry cycles: six, twelve, twenty-four and forty-eight (Table I).

Program 2 (wet-dry) was also performed on 4 sets of 6 specimens each, for a total of 24, but called for more severe conditions. Immersion times were longer, 20 minutes, and air-drying time was reduced to only 24 hours. The four different sets were subjected to six, twelve, twenty-four and forty-eight cycles (Table II).

Specimen immersion was performed in tubs filled with water at a temperature of 15° C.

Table 1: Program 1 (Wet-Dry)

Set	Number of Specimens per set	Number of cycles	Water immersion times (min)	Air-drying times (hr)
W-D1	6	6	10	48
W-D2	6	12	10	48
W-D3	6	24	10	48
W-D4	6	48	10	48

Table 2: Program 2 (Wet-Dry)

Set	Number of specimens per set	Number of cycles	Water immersion times (min)	Air-drying times (hr)
W-D1b	6	6	20	24
W-D2b	6	12	20	24
W-D3b	6	24	20	24
W-D4b	6	48	20	24

Program 3 (freeze-thaw) was also performed on 24 specimens divided into 4 sets of 6 specimens each. One complete cycle lasted 12 hours: 6 hours at +50°C and another 6 hours at -8° C. The four different sets were subjected to twelve, twenty-four, forty-eight and ninety-six cycles (Table III).

Table 3: Program 3 (Freeze-Thaw)

Set	Number of specimens per set	Number of cycles	Total times (hr)
F-T1	6	12	24
F-T2	6	24	48
F-T3	6	48	96
F-T4	6	96	192

The weathering cycles were executed in a thermostatic treatment chamber equipped with an electronic control unit enabling automatic execution of preset thermal inversions, thereby guaranteeing precise regular temperature variations. The apparatus is able to guarantee a temperature variation of 1°C per minute.

2.4 Mechanical tests

After completion of the degradation cycles, the specimens were subjected to "shear" tests by means of a controlled-deformation press, operated manually with a screw-jack. Force was applied to the protruding minor surface of the middle brick through a steel distribution plate; the intensity of the applied load was measured by a 100 kN load cell. Any displacements of the test specimens in key points were revealed by 6 displacement transducers placed in correspondence to the upper surface of each of the three bricks making up the brick specimen: more specifically, a transducer pair was placed on each of the three bricks' upper surfaces in correspondence to the midline of each short side. Load-displacement values were measured for each stepwise load increase of 500 N (fig.3).

During all tests the values of the mechanical parameters deemed suitable to revealing the level of degradation suffered by the specimens were acquired in real time by means of the electronic control unit. For the purposes of the present study, the load-displacement diagrams relative to the head of the central brick are invested with particular significance, in that they describe (both quantitatively and qualitatively) the behavior of the specimens in response to increasing levels of degradation, as revealed by reductions in peak load.

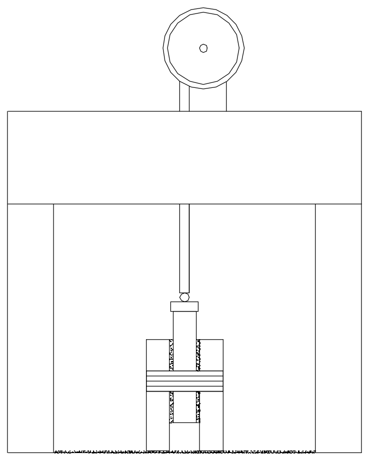

Figure 3: Testing apparatus

3 RESULTS

The results obtained with the "weathered" CFRC-reinforced specimens were compared with those recorded in two sets of 6 specimens that had not been subjected to any degradation cycles: a "control" set made up of 6 unreinforced samples and a "reference" set containing 6 reinforced specimens, which served to provide baseline data on the strength of such units. A particularly noteworthy finding is that the reinforced specimens exhibited peak load values that were double those of the unreinforced controls. The stiffness parameter was also 24% higher in CFRC-bearing specimens than in the controls.

The results obtained in the experimental trials on all 84 specimens have been summarized and presented schematically in the following diagrams.

The graph in figure 4 provides a comparison of the mechanical behavior of a typical unreinforced specimen with that of a reinforced one.

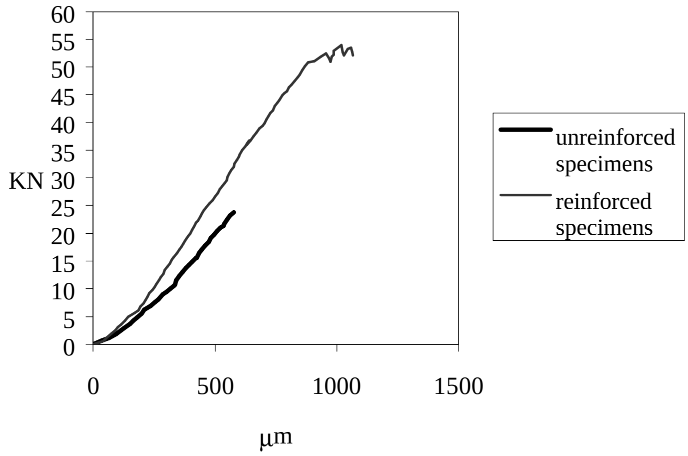

Figure 4: Load vs. Displacements

Figure 5 presents the mean values of the peak loads recorded for each single set subjected to wet-dry cycles. As is evident from the graph, for the more severely weathered sets a loss of resistance ensues almost immediately, that is from the 6th cycle on, and becomes practically constant by the 12th cycle, while for the sets subjected to less severe conditions, the initial loss of resistance is almost negligible. In every case, the 12th cycle represents a sort of cutoff point, in that no ulterior losses of resistance are recorded after its completion. Degradation therefore comes about immediately and leads to a constant loss of 18% by the 12th cycle for both weathering regimes.

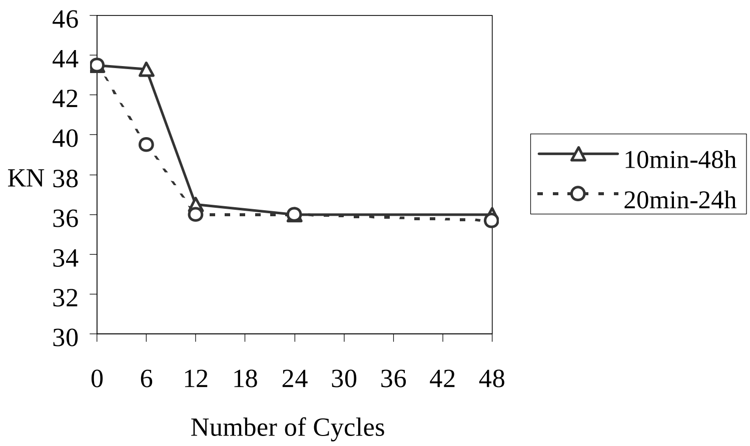

Figure 5: Effect of Wet-Dry Cycles

The mechanisms by which failure occurs, on the other hand, vary with increasing number of cycles to which the specimens are exposed: sets W-D1, W-D2, W-D1b and W-D2b exhibited breaking similar to that recorded in unweathered specimens; sets W-D3, W-D4, W-D3b and W-D4b were instead characterized by more fragile behavior and a wider area of detachment.

Nevertheless, we can safely state that the adherence between the CFRP reinforcement and the masonry demonstrated good resistance to alternating wet-dry conditions.

The results obtained with freeze-thaw cycles, instead, reveal progressive and continuous degradation of the resistance to shear, which eventually falls by 50% upon completion of the 96th cycle. Figure 6 presents the mean peak load values recorded for each single set subjected to cyclic freezing and thawing.

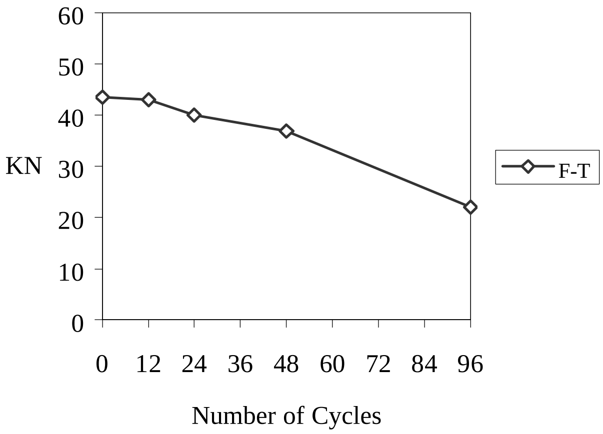

Figure 6: Effect of Freeze-Thaw Cycles

From the qualitative point of view, it can be observed that the specimens subjected to 12 and 24 freeze-thaw cycles do not evidence any signs of alterations of the contact surfaces. Moreover, the peak load values are only slightly lower than those recorded in unweathered specimens.

Considering the specimens subjected to 48 cycles, however, reveals quite a different situation: once extracted from the climatic cell, these present slight flaws on the extremity of the bond between the composite and brick, more precisely, beneath the primer layer. This cracking, which extended for a depth of a few millimeters, developed around the surface of the composite material. However, this brought about a reduction in resistance of only 15% of the initial level.

Far more evident flaws appeared on those specimens exposed to 96 freeze-thaw cycles. In this case, the effect was true detachment of the composite material from the brick (figg. 7-8). This first finding, arrived at by simply observing the specimens, was confirmed by the results of the mechanical tests, which revealed a 50% reduction in the peak load, that is to say, a fall to a level corresponding to that of the unreinforced specimens, a result in keeping with the fact that the reinforcement had already become completely detached.

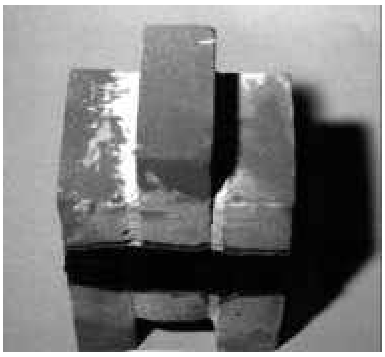

Fig. 7: Specimen after 96 Freeze/Thaw Cycles

Fig. 8: Specimen after 96 Freeze/Thaw Cycles

4 CONCLUSIONS

The described experimental trials were conducted in order to evaluate the effects of artificial weathering on the durability of masonry reinforced with CFRP strips. Because of the undeniable benefits consequent to such techniques, their use is currently on the rise. Nevertheless, it still remains to be seen whether CFRP reinforcements are able to offer the same level of performance in the long term as has been demonstrated in the short-term. Therefore, in order to better evaluate the potentialities of composite materials in masonry structural reinforcement, it seemed opportune to investigate the overall durability of brickwork masonry units strengthened with fiber-reinforced composite under hostile climatic conditions.

In assessing the reinforcing technique, the parameter that we assumed to be the most meaningful measure of its efficacy (or degradation) was the peak load, whose values for the reinforced units were sure to be influenced by the degree of adherence between the support and the reinforcement. A comparison study was therefore conducted to determine the differences in peak load values between variously weathered reinforced units and unweathered reference samples.

Table IV summaries the results obtained in the tests conducted on specimens subjected to artificial weathering cycles in the laboratory: the reduction in resistance is expressed as the percentage drop in peak load value with respect to unweathered reinforced specimens (i.e., the references).

Table 4: Averages of the reduction in resistance due Enviromental Conditions

Environmental Conditions	Loss of resistance
0 Cycles “Reference”	-
6 Cycles Wet/Dry 10′-48h	1%
12 Cycles Wet/Dry 10′-48h	17%
24 Cycles Wet/Dry 10′-48h	17%
48 Cycles Wet/Dry 10′-48h	17%
6 Cycles Wet/Dry 20′-24h	9%
12 Cycles Wet/Dry 20′-24h	17%
24 Cycles Wet/Dry 20′-24h	17%
48 Cycles Wet/Dry 20′-24h	18%
12 Cycles Freeze/Thaw	0%
24 Cycles Freeze/Thaw	8%
48 Cycles Freeze/Thaw	15%
96 Cycles Freeze/Thaw	49%

The following conclusions can be drawn from the results obtained.

- Exposure to alternating wet-dry has proved to have only a slight effect on the mechanical behavior of the specimens tested. In fact, such treatment determined a maximum decrease in resistance of only 18%. This rather modest loss was reached after only 12 cycles, after which the specimens' overall strength remained constant throughout the subsequent cycles (up to the maximum of 48).
- On the other hand, 96 cycles of freezing-thawing brought about total detachment of the composite CFRP material from the masonry, completely nullifying the reinforcement operation.

  Although limited in number, and performed through *ad hoc* procedures still in need of standardization, the experimental trials conducted have nevertheless served to underscore the need for further in-depth investigation of the durability of the bond between the masonry substrate and the reinforcement, especially when subjected to common environmental agents. In fact, the current findings indicate that even a limited number of some commonly recurring actions (e.g., freeze-thaw) can in a short time wholly cancel out the reinforcing effects obtainable through application of CFRP strips.

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