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# Influence of fibre reinforced polymers in the rehabilitation of damaged masonry wallettes

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## Abstract

In the past decade, the interest in repair and retrofitting of existing structures and rehabilitation of the damaged structures has led to the development of more effective and low invasive architectural and engineering strategies. In this aspect, the application of fibre reinforced polymer (FRP) strengthening techniques has become reasonably widespread as suitable solutions in addition to the traditional ones. They are promising techniques because of their key characteristics such as: high specific strength, high stiffness, small thickness compared to conventional materials, low influence on the global mass, little durability concerns, ease of handling, flexibility and fast installation that improve on-site productivity, and have a low impact on building functions. In this context, the use of carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) for the rehabilitation of damaged small masonry walls (here called wallettes) was investigated experimentally. This study sought to measure the maximum loading carrying capacity of the wallettes and to assess the possible structural rehabilitation in the damaged masonry structures after their reinforcement with the composite polymers. For the adhesion between the wallettes and the reinforcement fibres, primer, putty and a saturant glue epoxy resins were used. Debonding between the FRP composites and the substrate has been recognized as the primary failure mechanism of this reinforcement system and it occurs when the system shear capacity is reached and the FRP is detached from the element. This phenomenon is also addressed in this paper. In general, the experimental results showed the recovery of the original compressive loading bearing capacity of the structures, in spite of the debonding of the FRP composites. Moreover, it could be observed an increasing of up to 39% and up to 49% of the compressive strength for the damaged masonry wallettes reinforced with CFRP and GFRP systems, respectively. The recover (or even rise) in the loading capacity of the reinforced structures due to the external fibres bonding is a good indication of their effectiveness in these situations.

**Keywords:** Rehabilitation; CFRP; GFRP; Masonry; Damage

## Background

The structural masonry is a well-established traditional technology for the construction of affordable buildings. It is widely used throughout the world. Nowadays, simplicity and rationalisation of the construction process, aesthetic correctness, durability, low costs, good thermal and acoustic performance and fire resistance, among others, are characteristics that turn the masonry structures construction system into one of the most economical technology readily available [1]. In Brazil, structural masonry has been extensively used in the construction of the inexpensive buildings since the early

1960's and, up to now, represents one of the promising solutions for the housing deficit in the country.

Nonetheless, problems with structural pathologies, failures and collapses have been reported. They are the result of the lack of more rigorous quality control for the materials and inadequate production processes. In some cases, these problems also occur due to the application of inaccurate empirical dimensioning methods, without the wide use of computational tools, which would yield a more accurate structural analysis results. In addition to these factors, others contribute to aggravate these problems, such as: the application of unpredicted loads, due to different uses and architectural modifications of the structure; foundation settlement; wrong structural conception; natural deterioration of the materials and components; and, impacts, collisions or explosions. In such situations, the reinforcement or rehabilitation of the damaged existing structures have been, often, more attractive or desirable than replacing it with a new construction due to heritage, economic and environmental reasons [2].

The adoption of low invasive and high efficient strengthening techniques is one important aspect for the success and viability of the rehabilitation interventions. With this in mind, the usage of fibre reinforced polymers (FRP) to enhance the structural performance of masonry structures is a promising technique because of its high specific strength, high stiffness and small thickness compared to the conventional materials [3].

In the literature, numerous studies on the strengthening of reinforced concrete structures with externally bonded FRP sheets have been published for many years. However, only more recently, experimental and numerical researches have been conducted about the usage of the FRP for the structural rehabilitation and strengthening of masonry walls. Very good results have been reported, what contribute to the success on this approach [4-7]. Nonetheless, only few contributions refer to aspects concerning to the bonding and debonding behaviour between the masonry elements and the strengthening system.

The effectiveness of the reinforcement and the failure behaviour of fibre reinforced masonry structures are strongly influenced by the properties of the substrate where the reinforcement is applied. Therefore, this factor requires to be further explored. In fact, the stress concentrations occurring at the FRP/substrate interface could lead to the detachment of the reinforcement from the support and to the premature failure of the structure due to debonding [8]. The bonding behaviour of the FRP reinforcements on masonry surface has been investigated and theoretical formulations have been suggested by a specific Italian guide document, which are derived from the approach for concrete structures [9].

More recently, specific experimental tests were developed to investigate the nature of the bonding between composite reinforcements and masonry substrates. Moreover, the mechanism of debonding has been studied considering the influence of various factors, such as, bond length, geometry of the specimen, tests set-up, and type of the fibre reinforcing system. It also can be observed that the wide variety of the masonry substrates, formed by clay or concrete bricks (or blocks), affects the overall performance of the reinforcement system [10-14].

In this work, a set of small masonry walls was built using concrete blocks. Three specimens, considered as the reference ones, were subjected to axial compressive loading up to their collapse in order to induce damage to the wallettes. Seven other

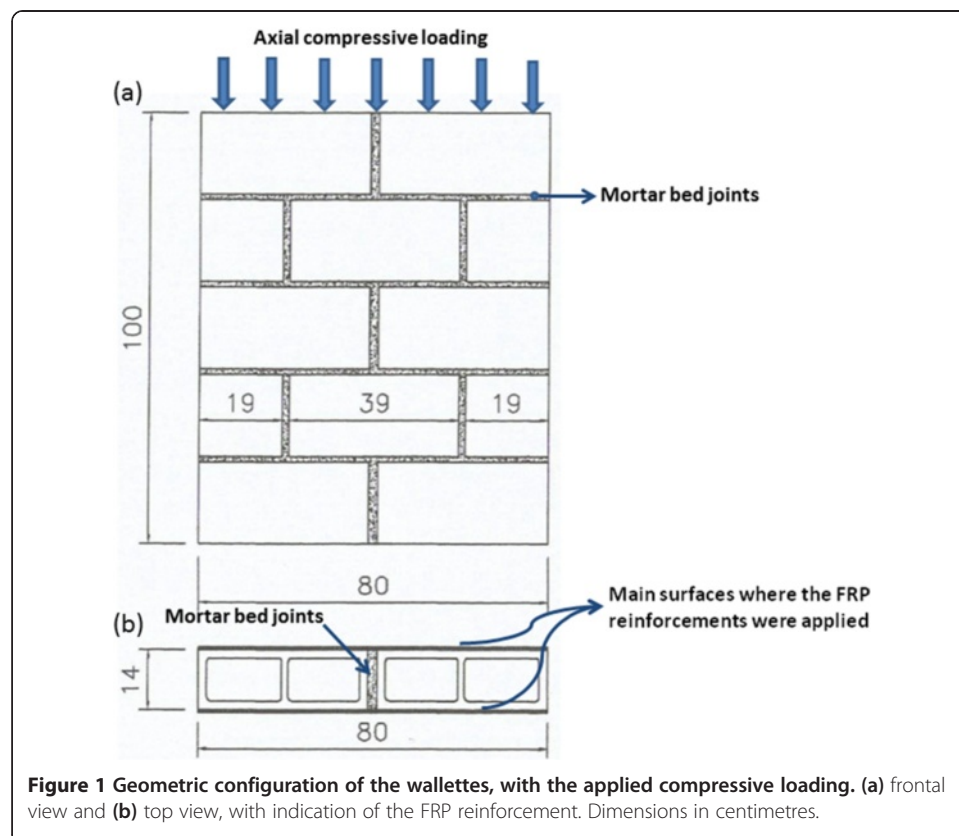
specimens were submitted to axial compressive loading of 75% of the average collapse loading of the reference wallettes. As far as the mechanical behaviour is concerned, masonry structures subjected to a loading of 75% of their failure threshold is considered to be completely (structurally) damaged, which can be characterised by the appearance of randomly distributed cracks or micro-cracks throughout the specimens.

The damaged specimens were then prepared and strengthened by the application of carbon fibre reinforced polymers (CFRP) or glass fibre reinforced polymers (GFRP), completely covering both their two main surfaces, as shown in Figure 1. An adequate chemical and physical bonding between the polymeric fibre and the substrate of the masonry was utilized. After the application of the reinforcement system, the wallettes were once again subjected to a vertical compressive load up to their collapse. This study measured the maximum loading bearing capacity of the wallettes and assessed the possible structural rehabilitation in the damaged masonry structures after the reinforcement with the FRP.

## Methods

### Materials characterisation and preparation of the specimens

The masonry wallettes used in this research were built using concrete blocks and 1:2:6 (cement: hydrated lime: sand) mortar and had the following dimensions: height = 100 cm; length = 80 cm; thickness = 14 cm, as shown in Figure 1. Two different block sizes were utilised to build of the wallettes: (a) single-hole blocks (dimensions: 14 cm x



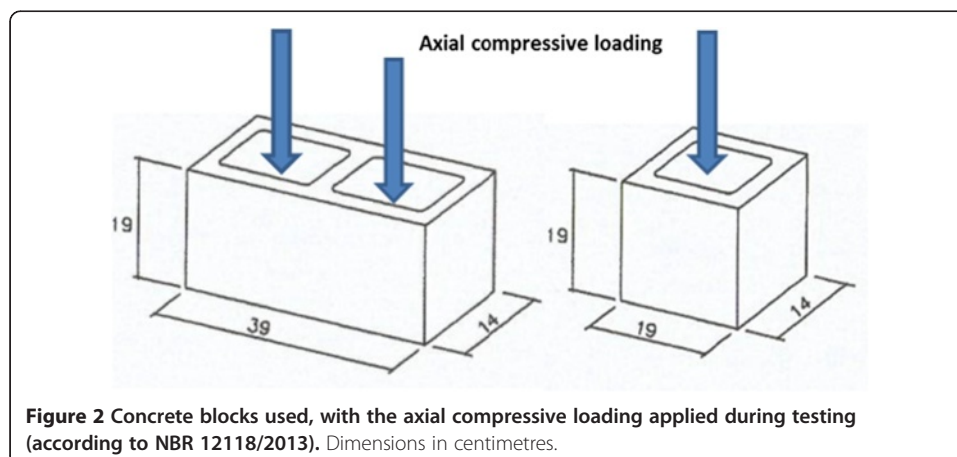
19 cm x 19 cm), and (b) two-hole blocks (dimensions: 14 cm x 19 cm x 39 cm), depicted in Figure 2, in order to allow the desired geometric configuration of the panels. Their average compressive strengths were, respectively, 6.30 MPa and 5.64 MPa. The mean compressive strength for the mortar specimens was 6.49 MPa. The experiments for the characterisation of the mechanical properties of these materials were conducted according to the Brazilian standards NBR 12118/2013 [15] and 13279/2005 [16], respectively.

Three specimens of the wallettes, namely RW1, RW2 and RW3, were built as schematic illustrated in Figure 1. Subsequently, they were subjected to axial compressive loading up to failure, which meant a mean load of 427 kN. The load was applied perpendicularly to the bed joints, in increments of the 2 kN, in an universal testing machine under vertical displacement control. During the loading, the strains along the loading axis were calculated using the average displacement measurements obtained from four dial gauges placed in the panels, two in each of the main sides. The test setup was established in accordance with the Brazilian standard NBR 15961-2/2011 [17]. These samples were considered the reference wallettes.

In order to cause damage to the wallettes, the seven remaining specimens were submitted to axial compressive loading of 75% of the average collapse loading of the reference wallettes, which resulted in a load of 320 kN. The loading was applied in the same direction as above. The applied loading was big enough to damage the specimens, as desired. From the visual inspection, micro-cracks and cracks could be observed in the blocks and the mortar joints of the structure, i.e., the wallettes were in fact damaged.

#### Characteristics and mechanical properties of the resins and fibre reinforcement polymers

The reinforcement system was made of polymeric fibre (FRP) and resins. The main mechanical properties of the FRP used in this work, given by the producer [18], were: for the CFRP (one-directional fabric mesh), Young's modulus  $E = 227$  GPa and tensile strength  $f_t = 3800$  MPa; and, for the GFRP (two-directional fabric mesh),  $E = 68.9$  GPa, and  $f_t = 1517$  MPa. Epoxy resins provided the bonding for the reinforcement system. The resins used were a primer, a saturant and a leveling compound called putty. They



are all two-component materials consisting of resin and hardener. Their main characteristics and mechanical properties are given in Tables 1,2,3.

#### Preparation of the masonry substrate and application of the reinforcement

Before the application of the fibre reinforcement, the wallettes were prepared using high pressure water blasting in order to remove the powder and any other particles from the substrate. They were dried in room temperature for 7 days. Subsequently, the damaged specimens were strengthened by the application of one-directional fabric of CFRP. These wallettes were denominated CW1, CW2, and CW3. The specimens GW1, GW2, GW3 and GW4 received two-directional fabric of GFRP. The FRP layers covered both the two main surfaces of all damaged specimens, according to Figure 1.

An adequate chemical and physical bonding between the FRP and the substrate of the masonry was established. Firstly, the substrate of the wallettes was prepared with the application of one layer of the primer. This primer is a two-component solvent-less epoxy system which when mixed yields a penetrating medium viscosity compound. This primer is used to penetrate the pore structure of the cementitious substrates and to provide a high bonding base coating for the FRP system. The drying of the primer on the substrate took around 1 hour in room temperature. Figure 3 illustrates the primer application. Since the damaged wallettes did not present crushed parts, only cracks or micro-cracks, there was no need to fill the collapsed regions with mortar.

Within a 48-hour period after the drying of the primer, a second layer of the adhesion system was applied, with a thickness of around 2 mm. This epoxy resin is known as putty. It was useful for the regularisation of any small surface imperfections and to provide a smooth surface to which the reinforcement system would be applied. The drying/hardening of the putty is an exothermic process that lasts around an hour. Figure 4 depicts the substrate regularisation when the putty was used.

The system was glued with a resin denominated saturant applied in two coatings, again within a 48-hour period to ensure the proper adhesion. This saturant is epoxy based, solvent free, high strength adhesive. One layer is applied over the primer, or the putty, already dried. At around one hour, before the saturant became tacky, the FRP fabric was applied. Within 2 hours, a second layer of saturant was applied on top of the FRP (Figure 5). Finally, a roller was used to expel any bubbles (Figure 6). The whole cure process took 7 days in room temperature, ranging between 25 to 35°C.

**Table 1 Characteristics and mechanical properties of the primer**

<i>Properties</i>	<i>Compressive</i>	<i>Tensile</i>	<i>Flexural</i>
<i>Yield strength</i>	26.2 MPa	14.5 MPa	24.1 MPa
<i>Strain at yield</i>	4.0%	2.0%	4.0%
<i>Elastic modulus</i>	670 MPa	717 MPa	595 MPa
<i>Ultimate strength</i>	28.3 MPa	17.2 MPa	24.1 MPa
<i>Rupture strain</i>	10%	40%	Large deformation with no rupture
<i>Poisson's ratio</i>	–	0.48	
<i>Pot life</i>	40 min at 25°C		
<i>Cure</i>	Fully cured at 20°C - 7 days		

**Table 2 Characteristics and mechanical properties of the putty**

<i>Properties</i>	<i>Compressive</i>	<i>Tensile</i>	<i>Flexural</i>
<i>Yield strength</i>	22.8 MPa	12.0 MPa	26.2 MPa
<i>Strain at yield</i>	4.0%	1.5%	4.0%
<i>Elastic modulus</i>	1076 MPa	1800 MPa	895 MPa
<i>Ultimate strength</i>	22.8 MPa	15.2 MPa	27.6 MPa
<i>Rupture strain</i>	10%	7%	7%
<i>Poisson's ratio</i>	–	0.48	–
<i>Pot life</i>	40 min at 25°C		
<i>Cure</i>	Fully cured at 20°C - 7 days		

The wallettes GW1, GW2, CW2 and CW3 were treated with the putty regularisation. The remaining walls, CW1, GW3 and GW4, did not receive the putty treatment.

The main direction of the fibre was positioned horizontally in the walls, that is, in the direction perpendicular to the axial loading application. This configuration was chosen so that a more effecting enveloping (or confining effect) in the damaged structures could be obtained. The enveloping mentioned above can be understood as the wrapping effect on the wallettes, based upon the hypothesis that the thickness of the walls is much smaller than the FRP covered surfaces. As a result of such a configuration, an increase in the compressive strength and the shear capacity of the structures was expected.

#### **Axial compressive loading experiments**

After the application of the reinforcement system onto the damaged wallettes, they were again subjected to a vertical compressive loading, up to their collapse. In this second loading, the relative vertical displacement was measured until the total load reached approximately 250 kN, which was around 60% of the reference collapse load. This procedure prevented damage in the measurement equipment if a sudden structural fail should occur. The experiments were performed in accordance with the Brazilian standard NBR15961-2/2011 [17]. For comparison with the reference wallettes experimental results, the Young's modulus was also determined for these reinforced wallettes.

**Table 3 Characteristics and mechanical properties of the saturant**

<i>Properties</i>	<i>Compressive</i>	<i>Tensile</i>	<i>Flexural</i>
<i>Yield strength</i>	86.2 MPa	54.0 MPa	138.0 MPa
<i>Strain at yield</i>	5.0%	2.5%	3.8%
<i>Elastic modulus</i>	2620 MPa	3034 MPa	3724 MPa
<i>Ultimate strength</i>	86.2 MPa	55.2 MPa	138.0 MPa
<i>Rupture strain</i>	5.0%	3.5%	5%
<i>Poisson's ratio</i>	–	0.40	–
<i>Pot life</i>	45 min at 25°C		
<i>Cure</i>	Fully cured at 20°C - 7 days		

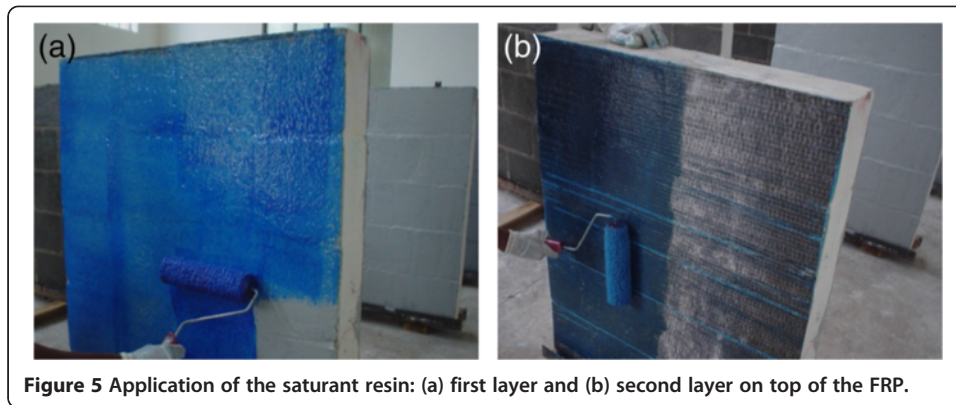




**Figure 3** Application of the primer on the damaged wallets.



**Figure 4** Putty application.



**Figure 5** Application of the saturant resin: (a) first layer and (b) second layer on top of the FRP.

## Results and discussion

### Axial compression results

The results of the experiments of specimens RW1, RW2 and RW3 under compression are shown in Table 4.

Tables 5 and 6 present the efficiency obtained in the compressive strength for each of the applied reinforcement systems when compared to the reference wallettes. It can be noted, in general, that all the tested specimens were able to recover the original strength (and even achieving higher values).

It can be seen from the tables that the specimens reinforced with CFRP that received the putty (CW2 and CW3) presented a much better performance in relation to mechanical resistance as compared to the wallette that was not prepared with the putty (CW1). The overall compressive strength gain was up to 39% for CW2 and CW3, whereas CW1 achieved roughly the reference strength, with a small 4% increase. On the other hand, the wallettes reinforced with GFRP presented non-uniform results, which does not allow for a definitive conclusion over their mechanical behaviour: the wallettes treated with putty presented a compressive strength increasing of 5% and 21%, while those that did not received the putty presented a strength improvement of 17% and 49%, as shown in Table 6.



**Figure 6** Roller used to expel bubbles.



**Table 4 Compressive strength of the reference wallettes**

<i>Wallettes</i>	<i>Compressive strength [MPa]</i>	<i>Average compressive strength [MPa]</i>	<i>Standard deviation</i>	<i>Variation coefficient [%]</i>
RW1	3.93	3.82	0.10	2.64
RW2	3.75			
RW3	3.79			

According to the manufacturers, the use of a proper adhesive system does not confer any extra mechanical strength to the FRP composite, but the adhesive is capable of creating a link between the substrate and FRP system and is able to distribute the applied loads. The above results confirm that the bonding between the FRP external reinforcement and the substrate is one of the key issues for the recovery of load capacity for reinforced structures [9,14].

#### Young's modulus and stress-strain behaviour

The Young's modulus was also determined for the reinforced wallettes and a comparison with the reference specimens was made. The results indicated that the reference (before reinforcement) and the FRP reinforced (after reinforcement) wallettes presented very similar behaviour under the compressive loading, as shown in Tables 7 and 8. These results suggest that the stiffness of the wallettes was also recovered after the application of the FRP reinforcement.

With regard to the stress-strain behaviour, the performance of the wallettes reinforced with CFRP was very similar when compared with their GFRP counterpart. Besides, both reinforcement systems presented stress-strain curves comparable to the curve for the undamaged specimens (before receiving the reinforcement), as depicted in Figures 7 and 8, indicating the rehabilitation of the strengthened structures.

#### Failure mode

From the experiments, it could be observed that a fragile, localised and sudden collapse occurred in the reference wallettes. In the majority of the cases, the cracks started when the loading approached its failure limit, i.e., approximately 75% of the estimated maximum load. This confirms the low ductility of the walls and the well-known expected fragile behaviour of the masonry structures [19].

Moreover, from the experiments in this study, it could be observed that the FRP reinforcement applied did not exhibit, during the entire loading process, faults or fracture of the adherent that could be visible to the naked eye. Figures 9 and 10 show that the CFRP reinforced wallettes that received the putty treatment (CW2 and CW3)

**Table 5 Obtained efficiency of the wallettes reinforced with one-directional fabric of CFRP**

<i>Wallettes</i>	<i>Set up</i>	<i>Achieved maximum strength [MPa]</i>	<i>Reference strength [MPa]</i>	<i>Efficiency</i>	<i>Standard deviation</i>	<i>Variation coefficient [%]</i>
CW1	Without putty	3.96	3.82	1.04	0.77	15.84
CW2	With putty	5.27		1.38		
CW3		5.31		1.39		

**Table 6 Obtained efficiency of the wallettes reinforced with two-directional fabric of GFRP**

<i>Wallettes</i>	<i>Set up</i>	<i>Achieved maximum strength [MPa]</i>	<i>Reference strength [MPa]</i>	<i>Efficiency</i>	<i>Standard deviation</i>	<i>Variation coefficient [%]</i>
GW1	With putty	4.02	3.82	1.05	0.72	15.28
GW2		4.62		1.21		
GW3	Without putty	4.46		1.17		
GW4		5.71		1.49		

presented failure of the reinforcement system only after the total collapse of the structures, without presenting fibre debonding, neither between the FRP and the adhesive system, nor between the concrete substrate and the adhesive system. The failure mode of the specimen CW2 (Figure 9) suggests that the fibre reinforcement allowed for the structural masonry wallette to reach its maximum working loading capability, even after suffering the imposed damaging. Figure 10 brings the failure mode of the CW3 structure, where the fragile rupture of the concrete blocks can be seen. Here, again, no debonding between the substrate and the adhesive or between the adhesive and the FRP can be observed. This fact, combined with the maximum loading bearing capacity shown by the CW2 and CW3 specimens (as in Table 5), implies that the application of the putty contributes to the rehabilitation, as well as to the increase of the loading bearing capacity, as the result of a better bonding of the reinforcement system to the substrate. However, the CW1 specimen (Figure 11) that did not receive the putty treatment offered a premature failure when compared with the specimens CW2 and CW3, as shown in Table 5. From this figure, it is possible to observe the debonding of the reinforcement fibres, when the wallette reached its original failure loading, i.e., the lack of bonding of the FRP limited its performance and it only displayed a small loading capacity improvement.

The experimental results confirmed, in general, the recovery of the original compressive loading bearing capacity of the structures. Moreover, it could be seen an increasing of up to 39% and up to 49% of the compressive strength for the damaged masonry wallettes reinforced with CFRP and GFRP systems, respectively, as shown in Tables 5 and 6.

The ultimate load attainable by FRP reinforcement depends essentially upon the compressive and tensile strengths of the substrate. Debonding between the FRP composite and the substrate has been recognised as the principal failure mechanism of the reinforcement system. Debonding occurs when the system shear capacity is reached and the FRP reinforcement is detached from the element. Since the substrate is usually weaker than the glue and the reinforcement, failure is normally associated with the

**Table 7 Initial tangential Young's modulus for the wallettes reinforced with CFRP**

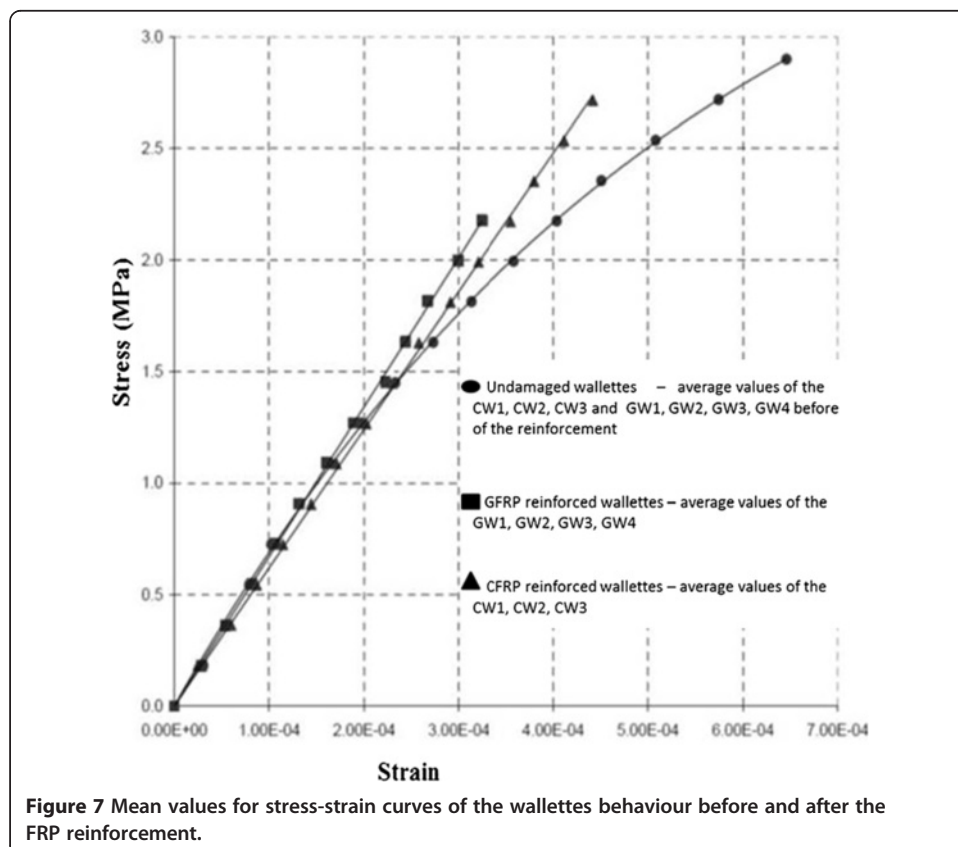
<i>Wallettes</i>	<i>Set up</i>	<i>Before of the reinforcement</i>			<i>After the reinforcement</i>		
		<i>E (MPa)</i>	<i>Average value (MPa)</i>	<i>Variation coefficient (%)</i>	<i>E (MPa)</i>	<i>Average value (MPa)</i>	<i>Variation coefficient (%)</i>
CW1	Without putty	5869	6100	8.50	5625	6170	8.38
CW2	With putty	6110			6653		
CW3		6320			6233		

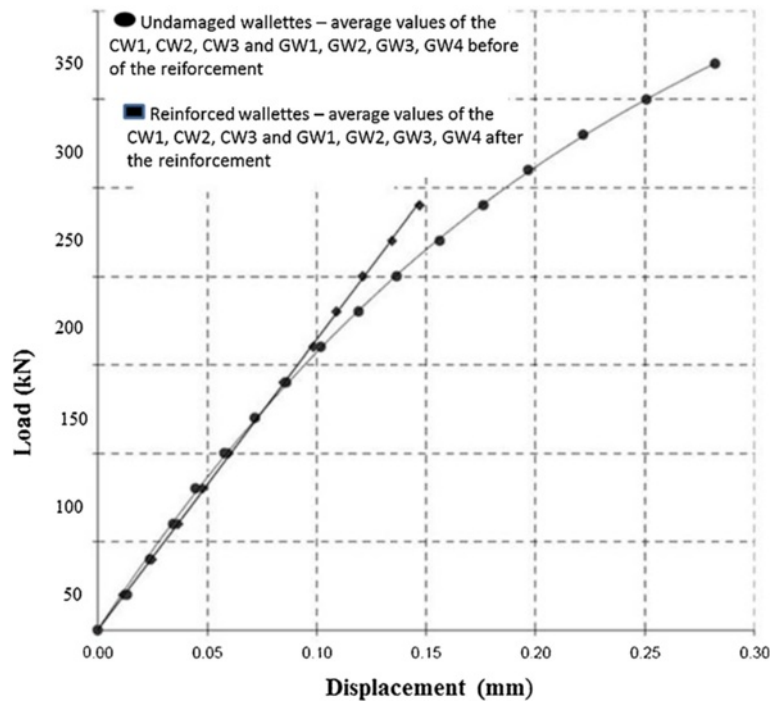
**Table 8 Initial tangential Young’s modulus for the wallettes reinforced with GFRP**

Wallettes	Set up	Before of the reinforcement			After the reinforcement		
		E (MPa)	Average value (MPa)	Variation coefficient (%)	E (MPa)	Average value (MPa)	Variation coefficient (%)
GW1	With putty	5890	7050	12.09	6117	6837	9.81
GW2		7078			6821		
GW3	Without putty	7927			6676		
GW4		7306			7734		

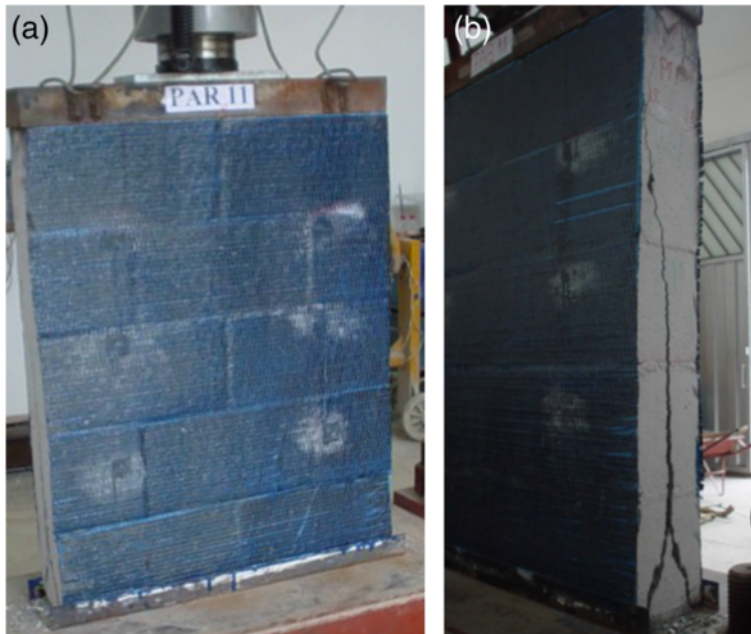
removal of a material layer during debonding. These behaviours have been widely studied for applications to concrete columns and beams, both from the experimental and numerical points of view, but, as far as masonry is concerned, only a limited number of studies can be found in literature [20]. In the current investigation, this fact can be observed and confirmed (see Figure 11).

In addition, it is believed that an “enveloping effect” was obtained with the FRP reinforcement. Also, the small confining action on the wallettes and, especially, the maintenance of the original geometry of the specimens were observed. These factors were considered responsible for the rehabilitation of the bearing capacity of the structures under the applied vertical compressive loads. The reinforcement application, and its potential of avoiding new cracks opening and the growth of the existing cracks, was also important to the final rehabilitation of masonry walls.





**Figure 8** Mean values for the load-displacement curves of the wallettes behaviour before and after the FRP reinforcement.



**Figure 9** Failure of the CW2 wallette reinforced with CFRP (with putty). (a) Frontal view and (b) lateral view.



**Figure 10** Failure of the CW3 wallette reinforced with CFRP (with putty).



**Figure 11** Failure of the CW1 wallette reinforced with CFRP (without putty).

Finally, it is relevant to comment that the long-term durability of the reinforced structures was not addressed in the current research.

## Conclusions

The main objective of this work was to present the rehabilitation potential offered by the CFRP and GFRP applied over previously damaged masonry wallettes. The wallettes were tested under axial compressive loading, before and after the application of the FRP reinforcement. It could be noted that the damaged, and later rehabilitated, wallettes could stand the maximum reference loading, with gains of 4% to 49% on the compressive strength in comparison with the measured failure loading of the undamaged reference wallettes. Both CFRP and GFRP reinforced wallettes showed load-displacement and stress-strain curves similar to those obtained from the reference wallettes. Debonding between the FRP composite and the substrate can be attributed as premature failure of the reinforcement system and, consequently, of the reinforced wallettes, as observed here. Moreover, the small confining action and the maintenance of the geometry contributed for rehabilitation of the damaged wallettes.

The increase in the load carrying capacity of the reinforced structures due to the external fibres bonding is a good indication of their effectiveness in these situations. Hence, the obtained results point out the potential and applicability of the FRP reinforcement system technique in full-scale problems for masonry structures.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

JSCN and GFM prepared the samples, ran the experiments and wrote the paper. Both authors read and approved the final manuscript.

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