The use of fibre reinforced polymers in the rehabilitation of damaged masonry wallets

Gray F. Moita
Júnia S. N. Chagas
Flávio A. Santos
Felício B. Barros

Como é de conhecimento comum, alvenaria estrutural possui características muito particulares quando comparada com outros sistemas estruturais. Além de serem responsáveis pela subdivisão de espaços, paredes de alvenaria estrutural são também responsáveis pelo suporte e redistribuição das cargas impostas ao sistema. Assim, qualquer dano nos seus componentes pode causar grandes problemas na estrutura como um todo. Polímeros reforçados por fibras ou *Fibre reinforced polymers* (FRP) podem ser aplicados para reforçar estruturas de concreto. Neste trabalho, FRP foram empregados na recuperação de painéis de alvenaria estrutural previamente danificados. O reforço foi aplicado em ambos os lados de estruturas submetidas a carregamentos compressivos, que foram ensaiadas em laboratório. Posteriormente, o comportamento das mesmas estruturas foi simulado por elementos finitos, com a incorporação de um modelo de dano. Os resultados computacionais foram comparados com os dados experimentais obtidos e apresentaram boa concordância.

Palavras-chave: Reabilitação; FRP; Dano; Simulação Computacional.

1 INTRODUCTION

Simplicity, rationalisation of the construction process, aesthetic suitability, durability, low maintenance costs, good acoustic characteristics and fire protection, among others, are features that turn the masonry structures construction system into one of the most competitive technology available (HENDRY, 2001).

In Brazil, in the 60’s, the structural masonry started to be used in large scale especially in the construction of low cost buildings. Even now, the constructions in structural masonry are presented as one of the promising solution for the housing deficit in the country.

However, a series of structural pathologies and collapses have been reported as the result of the lack of a more rigorous quality control for the materials and production processes employed, as well as, in some cases, due to the use of inadequate empirical design methods, without the use of computational tools for a more accurate structural analysis. In addition to these factors, others contribute to worsen the problems, such as: the application of unforeseen loads, due to different uses and architectural modifications of the structure; seismic and wind forces; foundation settlement;
inadequate structural conception; natural material degradation; and impacts or explosions.

From the above, there exists a clear need for the constant development of new technologies and materials for the recuperation, rehabilitation and reinforcement of masonry structures that are durable, reliable and still inexpensive so that damaged structures can be suitably treated.

In the present context, composites can be considered extremely efficient for engineering use, especially in reinforcement and retrofitting for structural applications. Studies point out a very attractive cost-benefit relationship. Fibre reinforced polymers – FRP – exploits the advantage of the high tension strength of the fibres, allied to the corrosion and fatigue characteristics, high stiffness and low weight. The carbon fibre reinforced polymers (CFRP), Glass fibre reinforced polymers (GFRP) and the aramid fibre reinforced polymers (AFRP) are the most commonly used composites for the structural reinforcement and rehabilitation (HOLWAY; HEAD, 2001; JAI et al., 2000; EINDE et al., 2003; KISS et al. 2002; SAADATMANESH, 1997).

This work presents the results obtained from the evaluation of the use of different techniques and materials for the rehabilitation of damaged masonry structure wallets under axial compression loads. FRP reinforcement was applied on the main surfaces of previously damaged specimens. Later, the specimens were subjected to a new axial loading in order to access the possible rehabilitation and their new load bearing capacity. The experiments were then reproduced numerically, using a finite element simulation with the introduction of the damage theory. The results were compared and analysed and interesting conclusion could be drawn, as shown in this paper.

2 METHODOLOGY AND EXPERIMENTAL PROGRAM

2.1 Physical and mechanical properties of the materials

A set of small masonry walls (wallets) were built using concrete blocks, with the following dimensions: height = 100 cm; length = 80 cm; thickness = 14 cm. Two different concrete block were utilised: (a) with a single hole (dimensions: 14 cm x 19 cm x 19 cm), and (b) with two holes (dimensions: 14 cm x 19 cm x 39 cm). The mean compressive strengths were, respectively, 6.30 MPa and 5.64 MPa. A 1:2:6 (cement: hydrated lime: sand) mortar was employed. The mean compressive strength of the mortar was 6.49 MPa. The experiments for the characterisation of the mechanical properties of the materials were conducted according to the Brazilian standards NBR 7184/82 (ABNT, 1982) and NBR 13279/95 (ABNT, 1995), respectively. The FRP used in this work were: CFRP (one-directional fabric mesh) and GFRP (two-directional fabric mesh), with nominal Young Modulus of E=240 MPa and E=68.9 MPa, respectively.

2.2 Experiments of the reference masonry wallets

Three specimens, namely PAR04, PAR08 and PAR09, were subjected to axial compressive load up to failure, according to the Brazilian standard NBR 8215/83 (ABNT, 1983). They were considered the reference wallets. The obtained mean axial compressive strength was then used as the reference for the following experiments with the reinforced wallets.

The stress-strain curve and the initial tangential Young modulus were obtained for each wallet separately. For the determination of the stress the gross cross sectional area was used and for the strain, the vertical displacements were measured. A least-square method was used to adjust the curve and obtain the desired straight line.

2.3 Experiments of the damaged and reinforced masonry wallets

In order to impose the expected damage, the specimens PAR03, PAR05, PAR07, PAR10, PAR11, PAR12 and PAR13 were also submitted in laboratory to the same axial compressive load described above.

The wallets to be damaged were subjected to an axial loading of 75% of the mean collapse load of the reference wallets, which means a total load of 320 kN. This loading was sufficient enough to establish a damage condition in the specimens, as desired. The actual damage could be seen in the walls as micro-cracks and cracks were formed in the blocks and the mortar joints. The Young modulus of the wallets was determined for the first loading.

The damaged wallets were then prepared and reinforced by the application of FRP overlaying both of their main surfaces, using an adequate chemical and physical bonding of the polymeric fibre and the substrate of the element to be reinforced.

The reinforced system was formed by two-part epoxy resins, composed by an epoxy primer that guarantees the bonding between the fibre and the actual wallet.

Later on, a polyester putty to fix the imperfections was applied (Figure 1). The wallets PAR03, PAR05, PAR11 and PAR13 were treated with the putty regularisation. The remaining walls, PAR07, PAR10 and PAR12, did not receive the putty treatment.

To glue the fibres another resin, called saturated resin, was applied in two coatings. The first one was...
applied over the putty regularised surface, as depicted in Figure 2, or directly over the wallets. And the second layer applied over the fibre itself (Figure 3).

Wallets PAR07, PAR11 and PAR13 were reinforced with a CFRP. The main direction of the fibre was positioned horizontally, that is, perpendicularly to the direction of the axial loading application, Figure 3. This configuration was chosen so that an enveloping effect in the damaged material could be obtained. The wallets PAR03, PAR05, PAR10 and PAR12 were reinforced in a similar manner, however this time with GFRP. The enveloping mentioned above can be understood as the wrapping effect on the wallets, once the thickness of the walls was much smaller than the covered surfaces. It was expected that it could increase the compressive strength and the shear capacity of the structures.

After the application of the reinforced of the wallets, once again they were subjected to a vertical compressive load up to collapse. In this second loading, the relative vertical displacement was measured up to approximately a total load of 250 kN, which is approximately 60% of the reference rupture load, so that the measurement equipment was not damaged. The experiments were performed in accordance with the Brazilian standard NBR8215/83 (ABNT, 1983). The Young modulus was also determined for these wallets and a comparison with the original (not reinforced) experimental results.

2.4 General considerations on the experimental results

2.4.1 Mechanical strength to axial compression

The results of the experiments of the specimens PAR04, PAR08 and PAR09 under compression, the so-called reference wallets, are shown in Table 1.

<table>
<thead>
<tr>
<th>Wallets</th>
<th>Compressive strength (MPa)</th>
<th>Mean value (MPa)</th>
<th>Standard Deviation</th>
<th>Variation Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR04</td>
<td>3.93</td>
<td>3.82</td>
<td>0.10</td>
<td>2.64</td>
</tr>
<tr>
<td>PAR08</td>
<td>3.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAR09</td>
<td>3.79</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tables 2 and 3 present, comparatively, the efficiency achieved in each of the applied reinforcement systems as the relationship between the attained compressive strength after the use of the rehabilitation and the compressive strength of the original reference wallets. It can be noted that, in general, all the tested specimens were able to recover the original strength, as compared with the reference established, and even achieved higher values.

It also can be seen that the specimens reinforced with CFRP that received the putty (PAR11 and PAR13) presented a much better performance in relation to mechanical resistance as compared to the wallet that was not prepared with the putty (PAR07), in spite the fact that, according to the manufacturers, the putty does not confer any extra mechanical strength to the composite. The overall compressive strength gain was up to 39%, whereas PAR07 basically achieved the reference strength, with a mere 4% increase, as in Table 2. This improvement can be explained by the enhanced bonding effect due to the regularisation of the original wall surface.

Nonetheless, the wallets reinforced with GFRP presented non-uniform results, which does not allow for a definitive conclusion over the general tendency of their mechanical behaviour. In other words, the wallets 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 3.

From the above, it would be hasty to draw any definitive conclusion over the influence of the use of the layer of putty in the overall maximum strength of the tested specimens. This can be a result of the small number of specimens used in the research, what made it impossible to obtain consistency in these results. New experiments are planned so that better and more comprehensive results can be set.

<table>
<thead>
<tr>
<th>Wallets</th>
<th>Preparation</th>
<th>Maximum strength (MPa)</th>
<th>Reference strength (MPa)</th>
<th>Efficiency</th>
<th>Standard Deviation</th>
<th>Variation Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR07</td>
<td>Without putty</td>
<td>3.96</td>
<td>3.82</td>
<td>0.77</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>PAR11</td>
<td>With putty</td>
<td>5.27</td>
<td>3.82</td>
<td>5.94</td>
<td>1.59</td>
<td></td>
</tr>
<tr>
<td>PAR13</td>
<td>With putty</td>
<td>5.31</td>
<td>3.82</td>
<td>5.94</td>
<td>1.59</td>
<td></td>
</tr>
</tbody>
</table>

2.4.2 Young modulus

The results for the Young modulus indicated that
the original and the reinforced wallets presented very similar behaviour under the compressive loading, as shown in tables 4 and 5.

The average performance of the wallets reinforced with CFRP was very similar when compared with their GFRP counterpart. Besides, both reinforcement systems presented average behaviour close to the average of behaviour of the whole set of specimens before and after the damaging process and the application of the reinforcement, as shown in figures 4 and 5.

<table>
<thead>
<tr>
<th>Wallets</th>
<th>Preparation</th>
<th>Before the reinforcement</th>
<th>After the reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E (MPa)</td>
<td>Mean value (MPa)</td>
<td>Variation Coefficient (%)</td>
</tr>
<tr>
<td>PAR11</td>
<td>With putty</td>
<td>6310</td>
<td>6100</td>
</tr>
<tr>
<td>PAR13</td>
<td>With putty</td>
<td>6320</td>
<td></td>
</tr>
<tr>
<td>PAR07</td>
<td>Without putty</td>
<td>5869</td>
<td></td>
</tr>
</tbody>
</table>

2.4.3 Failure mode

Figure 6 shows a fragile, localised and sudden collapse occurred in the reference wallets (without reinforcement). In the majority of the cases, the cracks started when the loading approached its limit, i.e., approximately 75% of the estimated maximum load. This confirms the low ductility of the walls and the expected fragile behaviour of the masonry structures (Lourengo, 1998).

From the experiments, it could be observed that the composite reinforcement applied did not exhibit, during the entire loading process, cracks that could be visible to naked eye. Figures 7 and 8 show that, when the failure of the wall did not occur in a localised manner, the reinforcement remained apparently unharmed, even after the collapse of the structure. On the other hand, when the specimen where not correctly aligned, a localised failure occur and there was a delamination of fibres in conjunction with the overall failure of the wall, as illustrated in Figure 9. Nevertheless, there was not such a delamination or failure in the composite coming directly from the applied loading. The expected behaviour of the failure mode can be seen in Figure 10, where the collapse and crashing of the internal cavities and scattered cracks in the overall structure are noted.

The experimental results obtained for the determination of the compressive strength and of the Young modulus indicated the actual rehabilitation of the previously damaged, and later reinforced, specimens, in addition to allow for the observation of the failure modes. It is believed that an “enveloping effect” was obtained with the composite reinforcement and that even the small confining action on the wall and, especially, the maintenance of the original geometry of the walls, were the main responsible for the rehabilitation of the bearing capacity of the structures under the applied vertical compressive load. The reinforcement application, and its capability of avoiding new crack opening and the growth of the existing crack, was also important to the final rehabilitation of the walls.

<table>
<thead>
<tr>
<th>Wallets</th>
<th>Preparation</th>
<th>Before the reinforcement</th>
<th>After the reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E (MPa)</td>
<td>Mean value (MPa)</td>
<td>Variation Coefficient (%)</td>
</tr>
<tr>
<td>PAR03</td>
<td>With putty</td>
<td>5890</td>
<td>7050</td>
</tr>
<tr>
<td>PAR05</td>
<td>With putty</td>
<td>7078</td>
<td></td>
</tr>
<tr>
<td>PAR10</td>
<td>Without putty</td>
<td>7927</td>
<td></td>
</tr>
<tr>
<td>PAR12</td>
<td>Without putty</td>
<td>7536</td>
<td></td>
</tr>
</tbody>
</table>

3 NUMERICAL SIMULATION

In order to better understand the rehabilitation obtained in the experiments, a numerical analysis using the finite element method was also performed. The degradation of the material (cracking) was simulated using the damage model by Simo (SIMO; JU, 1987), which, in turn, is based on the damage model of Mazars for concrete (MAZARS, 1984). The use of this theory tried to reproduce the degradation of the elastic properties of the material, here masonry, under loading.

The wallets were simulated with and without the CFRP reinforcement, however, using, for both situations, the theoretical damage process imposed by the constitutive damage model used. This was done with the intention of evaluating and comparing the damage reduction when the composite layers were applied.

3.1 General considerations on the computational analysis

The simulations indicated that the stresses and strains increase over the structures could be absorbed by the composite reinforcement, therefore avoiding the opening and the growth of the cracks. The low tensile stresses observed over the composite reinforcement confirm that the FRP applied provided a small but important confining action, as already concluded from the experimental results.

3.2 Masonry modelling
According to Lourenço (1996), the possible modelling strategies can focus either in the micro or in the macro aspects of the masonry. In the present work, micro-modelling was chosen. The concrete blocks and the vertical and horizontal mortar joints were separately modelled, however the interfaces between the joints and the blocks were not taken into account in the model.

The geometry, boundary and loading conditions used in the experiments were carefully reproduced. In the 3-dimensional modelling, shown in Figure 11, the mesh had 12556 elements and 13730 nodes. The finite elements used were enhanced 8-noded hexahedron elements (Lusas, 2004). The numerical load-displacement analyses considered the material damage initiating with 60% of the total reference failure load. An agreement in the results obtained numerically and experimentally was observed and can be seen in Figure 12.

3.3 Numerical analysis with the composite reinforcement

In the simulation of the FRP model, the reinforcement was modelled as a thin shell finite element placed on top of the 3-dimensional elements of the walls, using a linear elastic constitutive relationship.

The calibration of the load-displacement curve was based upon the experimentally obtained curves for the test-specimens. It is worth mentioning that the experimental load-displacement curves for both the original and the reinforced wallets were very similar (see Figure 4). The comparison between the numerical and experimental curves is presented in Figure 13. A good agreement can be noted in the portion of the curve monitored by the experiments. For more details on the parametric adjustment and calibration of the numerical model refer to Chagas (2005).

4 FINAL CONSIDERATIONS

The main objective of this work was to present the rehabilitation potential offered by the CFRP and GFRP applied over previously damaged masonry wallets. The wallets were tested under axial compressive loading, before and after the application of the composite reinforcement. It can be noted that the damaged, and later rehabilitated, wallets could stand the maximum reference loading, even with a gain of 4% to 49% on the compressive strength in comparison with the measured failure loading of the original undamaged walls. Both CFRP and GFRP reinforced wallets presented load-displacement and stress-strain curves similar to those obtained from the original wallets. The same occurred with the Young moduli obtained for the reinforced and undamaged walls. The small confining action and the maintenance of the geometry (without opening and propagation of the cracks) are believed to be responsible for the observed behaviour.

The analysis of both the experimental and numerical data allows for the above considerations. Also, the results can be regarded as good indication of the applicability of the technique in full-scale problems. Nonetheless, further research is needed in order to evaluate the behaviour of real structure in comparison with the wallets tested. In addition, the economic viability will also need to be assessed.

5 ACKNOWLEDGMENTS

The authors would like to acknowledge Degussa Construction Chemicals for the CFRP used in the experiments and Fapemig and CNPq for the financial support.

6 REFERENCES


ABNT. Brazilian Association of Technical Norms. Concrete block for masonry construction – Determination of the


FIGURES

Figure 1. Application of the putty over the damaged wallet.

Figure 2. Application of the first layer of saturated resin over the damaged wallet.
Figure 3. Application of the second layer of saturated resin over the damaged and fibre reinforced wallet.

Figure 4. Stress-strain curves of the wallets average behaviour before and after the FRP reinforcement.

Figure 5. Load-displacement curves of the wallets average behaviour before and after the FRP reinforcement.

Figure 6. Failure mode of wallet PAR09.

Figure 7. Failure mode of wallet PAR11.

Figure 8. Failure mode of wallet PAR11.
Figure 9. Composite reinforcement after the localised failure of wallet PAR13.

Figure 10. View of the internal aspect of PAR07 after the collapse.

Figure 11. Mesh and geometry of the 3-dimensional finite element discretisation.

Figure 12. Load-displacement curves with the numerical damage initiated at 60% of the theoretical failure load. Original undamaged wallets.

Figure 13. Load-displacement curves with the numerical damage initiated at 60% of the theoretical failure load. CFRP reinforced wallets.