EXPERIMENTAL INVESTIGATION ON BOND STRENGTH OF CFRP APPLIED TO MASONRY PRISM

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The externally bonded fiber-reinforced polymer is an innovative technique for enhancing the strength of masonry structures, however the link between fiber reinforced polymer (FRP) and the masonry presents the fragile zone. To improve the bond performance and to determine the influence of the unidirectional reinforcement bonded geometry on the local bond-slip behavior, this paper investigates the shear bond behavior of carbon fiber reinforced polymer (CFRP) laminate externally bonded to masonry prisms, to ameliorate their structural applications and to assess their effectiveness on the stress distribution and also on the load capacity along the bonded zone. The single-lap shear tests was performed on five unidirectional carbon fiber reinforced polymer laminate externally bonded on masonry prisms via epoxy adhesive. The failure modes and the displacement behavior analysis show that the strengthening system is most effective when enhancing the bonded surface, as it reduce the stress concentration along the bonded length and it increase the load bearing capacity .

Keywords: *CFRP, Masonry, Fiber-Reinforced polymer, Bond behavior, Strengthening, Single-lap shear test*

1. Introduction

Fiber reinforced polymer (FRP) is an innovative composite material characterized by its resistance at high temperature, its weight (which doesn't alter the structure mass), its capacity to enhance the seismic strength and the deformability of different structures.

The application of the Externally Bonded Fiber-Reinforced Polymer (EB-FRP) on constructions had considerably increased and it becomes an interesting technique for repairing or reinforcing different age's structures, it is an effective system for the rehabilitation of reinforced concrete structures [1]. The bond behavior and the force transmission of the composite laminate bonded to concrete substrate was evaluated by using the single-lap shear test [2 - 4]. Results indicated that the bond strength is influenced by the surface preparation, and there is an effective bond length above it, no additional increase in failure load can be attained [5]. For the bond behavior of CFRP sheets, the surface prepared by water jet had a multiplied capacity when it is compared to sandblasting [6]. In addition, the ultimate load depends on the fiber sheets stiffness; it increased when the fiber sheets stiffness increased [7]. The uses of FRP proved their effectiveness in improving the flexural and the shear strengthening of RC beams and in the confinement of the columns [8]. After their application on RC structures, it was extended to masonry constructions, which presents an important percentage of heritage, and exhibit after moderate or severe earthquakes many damages. FRP composite can be applied to masonry surfaces either with mortar or epoxy resin [9].

The EB-FRP are the most adopted systems used to reinforce RC structures, however few researches investigated the results of using the EB-FRP to reinforce the seismic resistance of the masonry structures [10 - 12], diverse studies were performed to improve their in-plane and out-of-plane behaviors [13 - 15]. The effect of diverse configurations and the applications of the EB-FRP on the out-of-plane and in-plane behavior of URM walls was evaluated by [16 - 18]. Triantafillou [19], had performed the in-plane and the out-of-plane tests on reinforced walls, the failure due to the out-of-plane loading is caused by the masonry crushing, however for the specimens under in-plane loading the failure was remarked after the delamination of CFRP.

The bond behavior between composites and substrate is one of the issues that influence the effectiveness of the reinforcement system [11]. Masonry reinforced with FRPs is characterized by a brittle failure, and especially when the epoxy resin adhesives were used, because it generates stress concentrations in the masonry [20]. Experimental results showed that the predominant failure is the debonding of FRP, additionally the bonded length didn't influence the ultimate load, which prove that there is a bonded length where no additional stress is transmitted [21, 22].

During the single-lap shear tests performed on the GFRP, CFRP, SRP (steel) strips and BFRP bonded to the bricks; the failure occurred by the FRP detachment with the removal of a thin layer of the masonry material [23]. The complete debonding of the composite from the substrate was remarked before it reached its maximum tensile strength. Limited tests were performed on FRP-to- masonry

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bond behavior, and especially on the clay brick types [24 - 29].

This work presents an experimental program to investigate the different debonding mechanisms; the effect of the CFRP bonded geometries on the failure pattern and on the ultimate load. The single-lap shear tests were performed on five masonry prism with different CFRP laminate geometries.

2. Experimental program

2.1 Materials Characterization

Materials characterization was conducted according to different test standards. The clay brick units were tested in compression, then five normalized mortars were tested in compression, and other three specimens of mortar were tested in flexion. For the masonry prisms, three specimens were subjected to compression perpendicularly to the mortar joints; all the results are illustrated in Table 1. For the impregnated CFRP wrap, six samples (Figure 1) with dimension of 250*15mm were tested in tension, the average results according to different standards are illustrated in the Table 2 and Table 3. The properties of the used adhesive are shown in Table 4.

2.2 Specimens preparation

Before the application of CFRP wraps, the surface of the six masonry prism, which constitutes of five units of clay brick units with dimensions of 240*115*64mm linked by mortar joints of 10mm were prepared correctly to enhance the integrity and to avoid the debonding of the CFRP systems.

After 28 days, the surfaces of the bonded zone were prepared by sand paper to remove extra mortar in the joints, and then they were brushed and wetted. The test region irregularities were prepared by applying a thin layer of epoxy primer by using a small paint roller to penetrate the product to the surface followed by a layer of mortar to avoid the influence of the surface and to ensure an accurate bond behavior between the CFRP laminate and the masonry. All the specimens were cured for 28 days (Figure 2).

Table 1

Properties of different materials

Material types	Dimensions (mm)	Type of test	Standard	Compressive strength (N/mm²)
Mortar (Applied on joints)	40*40*160	Flexural and compression strength	EN 1015–11 [30]	4.47
	50*50*50	Compression strength	ASTM C109/C109M [31]	3.31
Mortar (Applied on wall surface)	40*40*160	Flexural and Compression strength	EN 1015–11[30]	27.84
	50*50*50	Compression strength	ASTM C109/C109M [31]	13.85
Clay bricks	240*115*63	Compression strength	ASTM C-67 [32]	11.28
Masonry prism (3 bricks linked by mortar)	240*200*63	Compressive test	ASTM C1314 [33]	10.83
Masonry prism (2 units of brick linked by mortar)	240*130*63	Bond strength of mortar-masonry	ASTM C952 [34]	17.43

Table 2

Properties of fibers according to ISO 10618 [35]

Type of material	Fibers density	Thickness of CFRP wrap	Tensile strength (N/mm²)	Tensile modulus of elasticity (N/mm²)	Elongation at rupture
CFRP	1.82 g/cm^3	0.129 mm	>4000	230000	1.7 %

Table 3

Characteristics of fibers according to EN 2561 [36]

Type of material	Tensile strength (N/mm²)		Modulus of Elasticity in Tension (KN/mm²)		Nominal thickness (mm)
	Average	characteristics	Average	Characteristics	
Laminate	3500	3200	225	220	0.129

Table 4

Properties of adhesive

	Type	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)
Adhesive	Sikadur 330	0.5-0.9	30	4.5	0.9

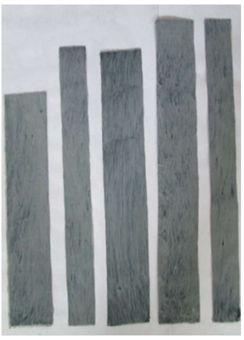


Fig. 1 - CFRP Laminate.

Fig. 2 - Bonded length prepared before the application of laminate.

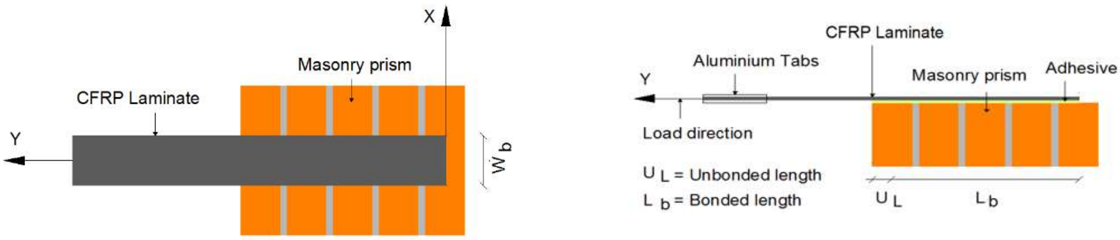


Fig. 3 - Geometry of the specimen.

Fig. 4 - Different specimens ready for testing.

Each length of the CFRP laminate was bonded starting from a distance of 30mm from the brickwork edge by using epoxy adhesive in the longitudinal direction. Reinforcement composites were applied following the indications provided by [30 - 31]. Tests were performed on different geometries of CFRP laminate to test the effective ones and to evaluate the size effect on the bond behavior between CFRP laminate and masonry prism. Two steel plates were bonded with epoxy over the laminate unbounded extremities to ensure the fixation and the total transmission of the tensile forces during the load application (Figure 3 and Figure 4).

2.3. Test Setup

The single-lap shear bond tests consists of CFRPs laminate prepared according to the wet lay-up technique bonded via epoxy adhesive to the masonry prism. The laminate size effect was investigated by adopting five different bonded widths and lengths. The bonded length for the specimens MP1-80 and MP2-50 corresponds to four bricks and four joints, for the other specimens MP3-80 and MP4-50 it corresponds to three bricks and three joints, for the last one MP5-80 it corresponds to two bricks and two joints, for the bonded width it varied between 50 and 80 mm.

A special care was given to the transportation of the specimens to avoid any deterioration of the laminate or of the masonry prisms in order to ensure the accurate transmission of the tensile forces to laminate during the load application. The steel plates bonded on the laminate extremities were fixed to the lower machine's head.

The bond tests were performed by using the universal machine, load was applied via a hydraulic jack linked to hydraulic pump with maximum load capacity of 50KN. A steel frame is utilized to correctly support the specimens and to avoid their displacements while applying loads, after their fixation on the steel frame, they were tested at a rate of the displacement ratio of 5um/s. The applied load is measured by a load cell.

A series of tensile forces were applied to the retrofitting system until it reached the post peak load. The bond strength was evaluated through the displacement between the laminate and the masonry prism. Test results of the peak loads and the different failure modes for each specimen will be summarized in the next part.

3. Results

The single lap shear tests were performed on carbon fiber reinforced polymer laminate bonded via an adhesive to a masonry prism substrate to evaluate their bonded behavior. An increasing tensile force was applied to different specimens. A brittle failure related to a complete debonding of the composite was remarked for all the tested specimens, which was caused by a sudden loss of the load bearing capacity.

During tests, while increasing the applied load progressive delamination of the reinforcement from the substrate was remarked, in some cases it was accompanied by the detachment of a thin layer of adhesive, or crack propagation at the laminate along the bonded length or the combination between them.

A remarkable decrease in the peak load resulted by the reduction of the CFRP laminate surface applied at the masonry prism. Otherwise, the degradation can be attributed to the micro cracking occurred in the matrix or at the fiber-epoxy interfaces.

The response to single-lap shear tests showed different maximum load bearing capacities and the cyclic loadings induced a high stress and caused the CFRP laminate delamination from the masonry prism during the tests.

A first comparison was between the specimens of the group A; all the CFRP laminate had a similar width of 80mm and different bonded length, respectively 300mm, 230mm, and 150 mm. Test results showed that the debonding force is directly related to the composite length, while increasing the bonded length the debonding failure changed from a brittle failure to a progressive and less brittle failure.

In the case of MP1-80, the strengthening system presented a high resistance before failure, with an average slip value of 1.73 mm, and a maximum load bearing capacity of 11.69 KN. The failure occurred at laminate-adhesive interface with partial debonding at the matrix-adhesive interface, the interface bond degradation can be attributed to the decrease of its stiffness. The specimen MP3-80 had different load-slip response, the maximum load reached in this case is 5.02 KN, less by 57.06% of the value of the specimen MP1-80. The failure occurred by the debonding of the CFRP laminate with partial debonding at the matrix-adhesive and fiber-matrix interfaces along the bonded length. The specimen MP5-80 load bearing capacity is 1.37 KN, the partial delamination started from the bonded length extremity, however, when the specimen reached the maximum load, a sudden degradation in the bonded strength resulted; the failure in this case was characterized by a brittle debonding of the laminate from the adhesive layer, with detachment of the fiber-matrix interface.

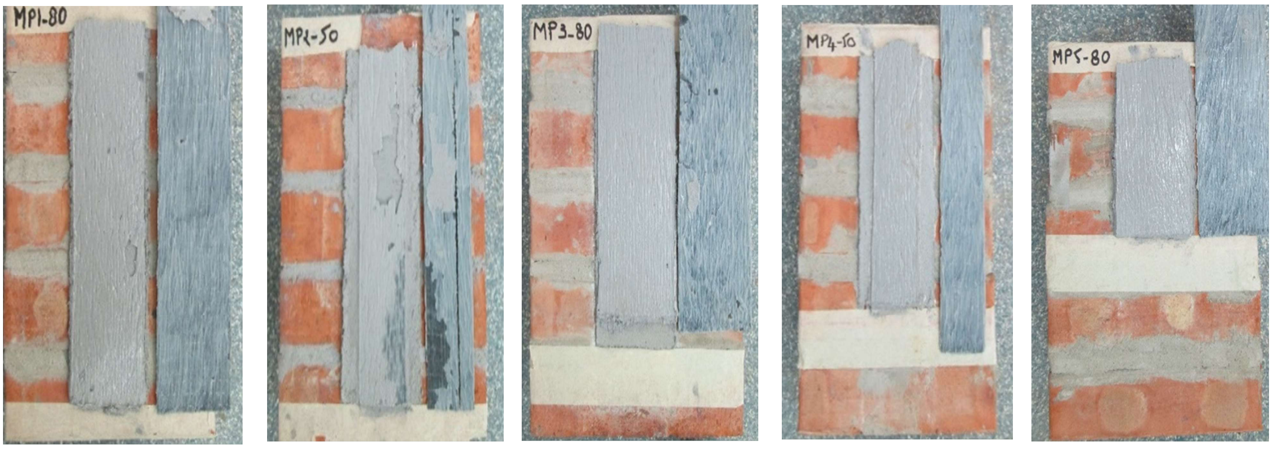
For the group B, the CFRP laminate had a similar width of 50mm, and different bonded length, respectively, 300mm and 230mm. The failure in the case of the specimen MP2-50 started by progressive debonding of the laminate then crack pattern were developed at the matrix-adhesive and at the fiber-matrix interfaces with the rupture of CFRP laminate, and propagated progressively along the composite and enhanced the laminate slip. For the last specimen MP4-50, the maximum load is 1.30 KN, the failure was occurred by the total delamination of the CFRP laminate and the partial debonding at the fiber-matrix interface.

The failure mode depends on the properties of the tested specimens, in general, after failure the visual inspection revealed the following debonding modes:

a. Debonding of the CFRP laminate,
b. Partial debonding at the matrix-adhesive interface,
c. Partial debonding at the fiber-matrix interface,
d. Rupture of the laminate.

It should be noted that other failures, such as the cohesive failure at the masonry substrate and the slippage within the matrix were not remarked.

Results showed that the failure mode is influenced by the bonded length L_b. The failure mode a and c observed in the case of the specimens MP4-50 and MP5-80, however the specimen MP1-80 and MP3-80 showed the combination of three failure modes (a, b and c), which corresponds to the total debonding of the CFRP laminate and the partial debonding at the matrix-adhesive and at fiber-matrix interfaces. Whereas in the case of the specimen MP2-50 in addition to the failure mode a, b and c, the laminate rupture is resulted. The Figure 5 shows the failure modes of different specimens.



MP1-80 MP2-50 MP3-80 MP4-50 MP5-80

Fig. 5 - Failure modes of different specimens.

The results showed a better performance of the CFRP laminate, in the case of the group A the load bearing capacity vary in a wide range between 11.69 KN and 1.37 KN, however for the group B it varied between 7.28 KN and 1.3 KN. The interface local behavior of the CFRP laminate of the group A is characterized by a high strength. The specimen MP1-50 had the less peak load and the maximum damages when it compared to MP2-50. For the specimen MP1 the CFRP laminate width variation from 80mm to 50mm showed diverse strength and load bearing capacities, the specimen with 50mm induced a higher decrease in strength.

Specimens with different bonded geometries were compared in terms of the peak load and strength. Test results showed that when increasing the bonded length L_b and width W_b, the strength and the load carrying capacity increased too. For the specimen length of 300 mm, the peak load was found about 37.72% higher when increasing the laminate width from 50mm to 80mm.

The load-slip response vary in function of the strengthening system geometry, the curves showed three principal stages, the first one is related to un-cracked step, the second one designated the behavior before the specimen achieved the peak load and the last one described the behavior from the post peak load until the specimen failure.

The response of the specimen at the beginning of the test is linear then it’s almost constant until the laminate reached its maximum resistance, then a sudden decrease in the load bearing capacity followed by a brittle interface failure started at the free edge and transmitted to the bonded length until the system reached its peak load.

The linear response of the load-slip curves is related to the elastic behavior between fibers and the matrix, which exhibit in function of time a micro-damages that alter the strength and the stiffness between the CFRP-matrix and between the laminate-substrate interfaces.

The results of the tested specimens in terms of the peak load and its corresponding slip are illustrated in the Table 5. The load-slip curves (Figure 6) illustrate the behaviors associated to each laminate geometry, in the most cases the failure occurred at CFRP-adhesive interface, however in some cases it was accompanied by shearing of a thin mortar and brick-mortar layer below the CFRP laminate.

Table 5

Geometry of CFRP and results of the tested specimens

Specimen	Unbonded length, U_L (mm)	CFRP bond width, W_b (mm)	CFRP bond length, L_b (mm)	Maximum Displacement (mm)	Failure load (KN)	Dominate failure
MP1-80	30	80	300	1.72	11.69	a+b+c
MP3-80	30	80	230	1.25	5.02	a+b+c+d
MP5-80	30	80	150	0.96	1.37	a+b+c
MP2-50	30	50	300	2.67	7.28	a+c
MP4-50	30	50	230	1.57	1.30	a+c

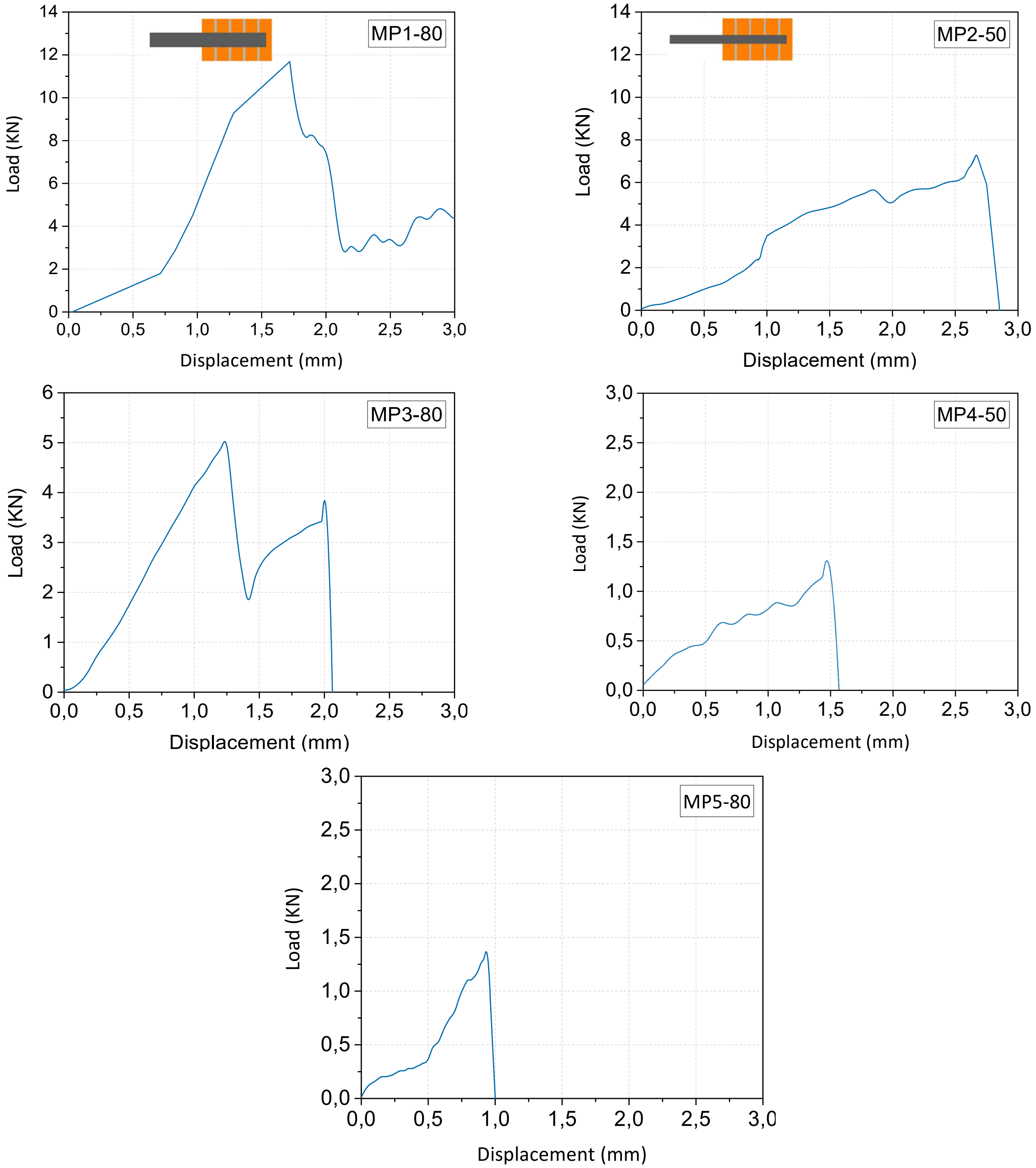


Fig. 6 - Load versus displacement curves.

4.Conclusion

The variation of the bond strength in function of diverse strengthening geometries was investigated to characterize the bond behavior of the CFRP laminate applied to masonry prisms and to increase the deformation, the load bearing capacity and the stress distribution along the bonded length. By evaluating the results of the bond behavior at CFRP laminate-masonry interface the following concluding remarks can be drawn:

The results of different specimens in terms of strength, load-displacement and failure modes showed an important contribution to understanding the mechanical behavior of the bonded CFRP laminate.

The stress transfer between the laminate and the masonry is different from a specimen to another. However, in all cases the interface failure started at the edges of the bonded length and propagated along the system until its failure.

The fatigue strength of the CFRP wrap composite depends on the matrix and on the prism surface stiffness and strength.

The fracture of CFRP laminate-adhesive interface is associated with the micro-crack formation in the matrix or in the fibers, and then interface cracks were propagated along the bonded length at the CFRP-matrix interface until the delamination occurred.

Different failure modes were observed, which were localized in many cases at the laminate-adhesive interfaces. In some cases, the combination between different failures such as partial debonding at the matrix-adhesive interface, partial debonding at the fiber-matrix interface and rupture of the laminate were occurred.

The failure modes were considerably affected by the laminate bonded geometry, which influenced the bond behavior and the capacity of the laminate in reinforcement. However, it exists an effective length beyond it no additional force is transmitted before the delamination.

The load responses of the tested specimens were approximately similar; indeed, the maximum load bearing capacity is higher for the laminate with the highest length and width. Furthermore, the mechanical properties of the laminate were not completely exploited in the case of a low ratio of reinforcement.

The improvement of the mechanical properties of the laminate is related to the effectiveness of the reinforcement system to transfer the force between the matrix and reinforcement by friction.

Based on the experimental results it can be concluded that the reinforcement bonded geometry can alter the debonding force, however, when the reinforcement width is insufficient to allow the full transfer of the loading forces an increase in width must be taken into consideration.

The relative slip of CFRP laminate depends on the bonded surface geometry. It was remarked that the load carrying capacity increased with the increase of the bonded length; nevertheless, beyond a certain length no enhancement of strength was occurred.

Further investigations are needed to evaluate the bond behavior of the composite-masonry interface, to determine the effect of the surface preparation, number of layers and the stiffness of CFRP on the bond performance.

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