GFRP-brick strengthening systems under high strain rates

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Abstract

Fibre Reinforced Polymers have become a popular material for strengthening of masonry structures. The performance of this technique is strongly dependent on the bond behaviour between the FRP and the substrate. Understanding the strain rate effect on the bond behaviour of this strengthening technique is important for proper design and proper modelling of these systems under impacts or blast loads. This work aims to study the bond behaviour between Glass Fibre Reinforced Polymers and brick at different strain rates. A Drop Weight Impact Machine specially developed for pull-off tests (single lap shear tests) is used with different masses and different heights introducing different deformation rates. The strain rate effect on the failure mode, shear capacity and effective bond length is determined from the experimental results. Empirical relations of dynamic increase factors for these materials and techniques are also presented.

Bond behaviour of GFRP-brick under high strain rates

In this work it is intended to study the effect of high strain rates in the bond behaviour of GFRP-brick strengthening systems. The main objective is to develop empirical relations, based on experimental results, able to relate the maximum bond capacity with the slip rate. These empirical relations are based on the DIF (Dynamic Increase Factor). During the tests both the load profile and slip profile are necessary. The load profile relates to the quasi-static reference allowing calculating the DIF (Eq. 1) and the slip profile allows calculating the slip rate as the gradient of the slip-time curve. Similar procedures were used previously (Hao and Tarasov [1], Lourenço and Pereira [2]).

$$DIF = \frac{Property\ (dynamic)}{Property\ (quasi\quad static)}, f(\delta) \tag{1}$$

Different test setups have been used to characterize the bond behaviour of concrete-FRP systems, some being already implemented in international standards such as the American Concrete Institute (ACI 440). In the case of masonry-FRP systems, due to the lack of standard test setups, similar setups have been used to study this phenomenon (Ghiassi [3]). Single-lap shear bond tests consist in imposing a load in the FRP strip, along its longitudinal direction. Usually, the composite is applied to one of the faces of the substrate, leaving enough FRP strip free to be connected to the actuators.

Ghiassi [3] studied the bond behaviour of GFRP-brick systems using single-lap shear bond tests under quasi-static conditions. These tests were performed with similar specimens to those studied in this work, using the same materials. These tests under quasi-static regime were performed using a servo-hydraulic actuator with a

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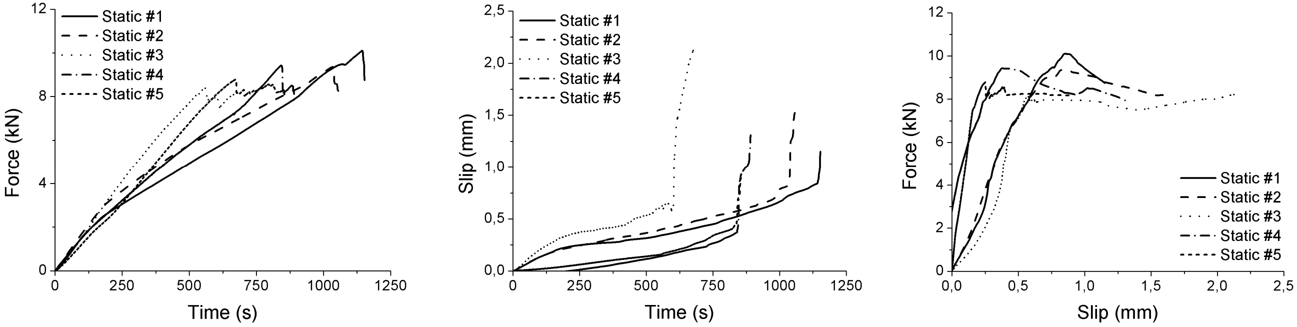
50 kN maximum capacity. The test specimens were placed in a steel support structure, specially designed for this purpose. The load profile was measured using a load cell and the slip was measured using several LVDTs placed along the reinforcement. Five tests were performed (Figure 1) averaging a maximum load of 9.22 kN (Figure 1a) and a maximum slip of 1.43 mm (Figure 1b). These tests were performed under a slip rate of around 10^{-5} mm/ms. These results are used in this work as the quasi-static reference for the DIF calculation.



a) b) c)

Figure 1: GFRP-brick quasi-static results: a) force-time profile; b) slip-time profile (Ghiassi [3]).

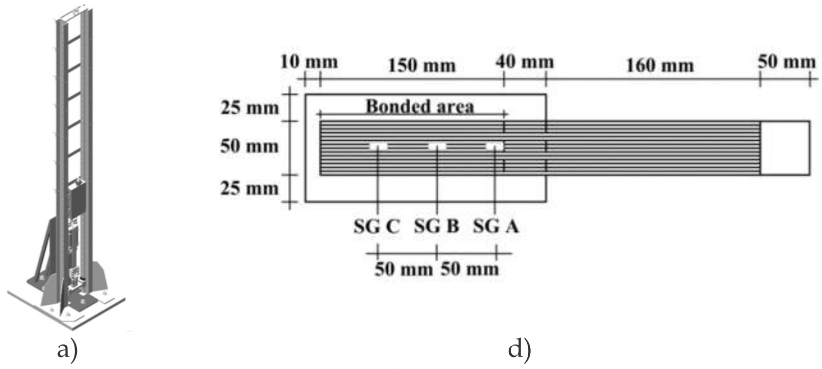
In order to study the bond behaviour of these systems under high strain rates, a new test setup was developed based on the drop weight concept. This new testing equipment and the obtained results are presented in the following sections.

Testing Equipment

A drop weight tower specifically developed for single-lap shear bond tests was used for the dynamic testing (Figure 2a). This tower allows a drop height up to 3 meters and a drop weight with a minimum of 14 kg.

The load profile was measured at the free end of the GFRP strip using a load cell specifically for dynamic applications – VETEK VZ101BH. This load cell is connected to a National Instruments Acquisition System. This acquisition system is composed of a SCXI-1000DC chassis, a SCXI-1600 data acquisition and control card for PC connection and a generic input module SCXI-1520 with a SCXI-1314 mount. The SCXI-1600 limits the sampling speed to 200 kS/s (200 samples per millisecond), which was found to be enough even at a later stage where 4 channels where used at the same time, allowing an acquisition frequency of 50 kHz per channel.

The deformation behaviour of the specimen was measured in two different ways. First, a FastCam video camera was used. It is a PHOTRON FastCam APX – RS with a maximum frame rate of 250 000 frames per second. This equipment allowed the visualization of the test in slow motion and the measuring of the slip. This slip measurement was possible using targets in the specimen at a specific location and performing a tracking sweep of those targets in the video. To perform the tracking sweep, the TEMA Tracking Software (v: 3.1-005) was used. With the relative position of the targets, the slip at each instance was calculated. The second methodology used to obtain the deformation behaviour was using strain gauges. The strain gauges used were BFLA-5-8-3L (Figure 2b) from TML and were the same used in the quasi-static testing performed by Ghiassi [3].



a) d)

Figure 2: Single-lap shear bond tests: a) drop weight tower; b) specimen schematics.

Specimens preparation

The application of GFRP reinforcement usually involves two steps: a) preparation of the substrate surface and b) application of the reinforcement. The preparation of the substrate surface, in this case clay brick, should be taken with special attention in order to obtain a good bond between the two materials (Juvantes [4]). The bricks used in this study, 200x100x55 mm bricks, were similar to those already studied and characterized previously by Lourenço and Pereira [2] and Ghiassi [3] under different conditions. Initially the bricks were grinded (approximately 7 mm) in the face where the reinforcement was applied, in order to improve the mechanical and chemical bond capacity of the application (Ghiassi [3]). After this initial treatment the bricks were washed and placed in an oven at 100 ºC for a period of 24 hours. After this period the specimens were removed from the oven and cleaned with compressed air, making sure that the surface was kept clear of any small particles.

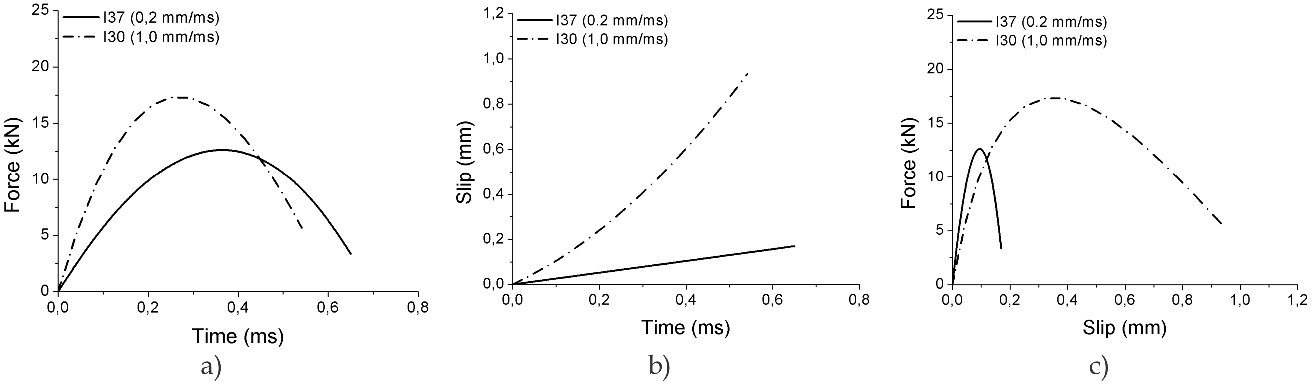
With the surface prepared, the reinforcement application can be initiated. Firstly, a primer is applied, only in the bonded area (the rest of the surface is protected with duct-tape) (Figure 2b). The applied primer was a MAPEWARP PRIMER 1 and the bonded area can be seen in Figure 7b. The GFRP reinforcement was composed of glass fibre MAPEWRAP UNI-AX and MAPEWRAP 31 epoxy. In order to apply the reinforcement, the procedure was the following:

a) Cut the glass fibres with the required dimensions (400x50 mm) and place two metallic sheets in one end of the fibres for bracing (Figure 2b);
b) In the brick surface a layer of epoxy is applied using a brush;
c) In the fibres a layer of epoxy is also applied and the fibres are placed in the correct position. In order to have full contact between the fibres and the surface a foam roll is used;
d) A new layer of epoxy is applied on top of the fibres and the foam roll is also used to have an even distribution of the epoxy;
e) After 60 minutes the duct tape is removed and the specimens are left to cure at ambient conditions for three weeks.

It should be noted that the bond behaviour of these strengthening systems is much dependant on the preparation of the specimens. Although the specimens used for impact testing were not from the same batch as the specimens used for the quasi-static tests from Ghiassi [3], the same procedure was used and the same technician supervised the preparation of both batches.

Impact tests

A total of 20 specimens were tested with the drop-weight tower developed for dynamic testing. Five tests were not considered in this document due to failure of acquiring data during the test. The hammer weight was kept at 14 kg and the drop height varied from 10 to 40 cm. By varying the drop height, different impact energies are introduced in the system leading to different strain rates. The acquisition sampling speed was kept at 24 kHz for the force and strain profiles and 12000 fps for the video equipment. Figure 3 shows two examples for low (I37 – 0.2 mm/ms) and high (I30 – 1.0 mm/ms) slip rates of force profile (Figure 3a), slip profiles (Figure 3b) and force-slip profiles (Figure 3c). Figure 4 shows the typical failure modes obtained in the dynamic single-lap shear bond tests, being similar to those obtained in the quasi-static tests by Ghiassi [3].



a) b) c)

Figure 3: Examples of impact test results: a) force-time profile; b) slip-time profile; c) force-slip profile.

a) b)

Figure 4: Examples of failure modes: a) total detachment of the fabric; b) partial detachment of the fabric.

Table 1 shows the results obtained for the dynamic tests on GFRP-brick systems. It can be seen that the maximum force ranged from 12.65 kN to 18.73 kN for slip rates of 0.06 mm/ms and 1.32 mm/ms, respectively. The slip rate was calculated as the gradient of the slip-time curve, similar procedure for strain rates was previously used (Hao and Tarasov [1], Lourenço and Pereira [2]).

Table 1: Impact tests on GFRP-brick specimens.

Specimen	Drop height (cm)	PHOTRON		Load cell	DIF	Failure mode (Detachment length)
		Maximum slip (mm)	Slip rate (mm/ms)	Maximum force (kN)		
Quasi-static [3]		1.49	2E-5	9.22	1.00	Total
I37	11	0.19	0.06	12.65	1.37	Partial 5cm
I41	15	0.32	0.07	14.97	1.62	Partial 5cm
I7	16	0.17	0.08	14.66	1.59	Partial 7cm
I25	14	0.14	0.09	13.16	1.43	Partial 5cm
I1	17	0.29	0.10	14.94	1.62	Partial 6cm
I20	16	0.45	0.13	14,85	1.61	Partial 6cm
I40	19	0.49	0.15	15.96	1.50	Partial 7cm
I26	21	0.41	0.25	16.81	1.82	Total
I3	18	0.53	0.44	17.66	1.92	Partial 5cm
I31	25	0.76	0.57	16.65	1.81	Total
I46	30	0.84	0.74	17.15	1.86	Total
I44	31	0.87	0.77	17.64	1.91	Total
I36	28	0.58	0.83	15.64	1.70	Total
I30	37	1.00	0.87	17.29	1.88	Total
I49	36	1.28	1.32	18.73	2.03	Total

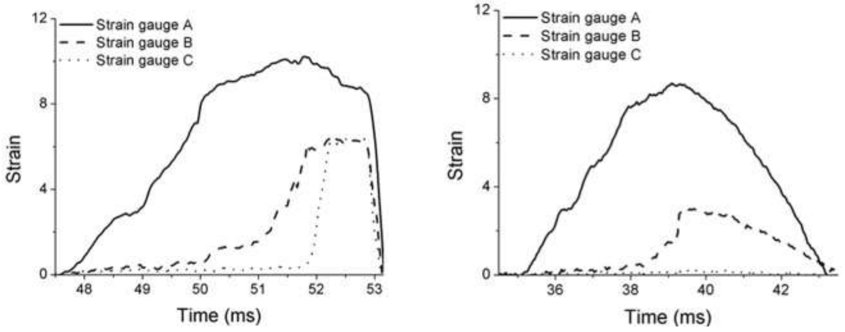
It is clear that the slip rate influences the bond behaviour of these systems. For slip rates of around 1 mm/ms the maximum force is about two times the maximum force obtained for the same system under quasi-static conditions. This is equivalent to a 14 kg mass being dropped at 40 cm. Using the quasi-static reference values from Ghiassi [3] it is possible to calculate a Dynamic Increase Factor, as the relation between both the reference and the dynamic test.

As stated previously, tests using strain gauges were also performed. The two main reasons for using the strain gauges are: (a) validate the video equipment acquisition system, by comparing the slip from the two different sources; (b) determine the effective bond length in this dynamic regime. Three strain gauges were placed in each specimen (50 mm spaced), as can be seen in Figure 2b. Figure 6 shows two examples of the results obtained with strain gauges, for total detachment of the fabric (Figure 6a) and partial detachment of the fabric (Figure 6b). As can be been in Figure 6 when the first strain gauge is in plateau at maximum strain, the next strain gauge is registering a very low strain value, close to zero. Knowing that the strain gauges are spaced 50 mm, the effective bond length was considered to be 50 mm or less. This result for the effective bond length is similar to the results obtained for the quasi-static regime, where the same value for the effective bond length was determined by Ghiassi [4] meaning that the slip rate does not influence the effective bond length of these systems. Because when there is a detachment longer than the effective bond length, the maximum force is already mobilized, this allow the inclusion of the experimental tests with a partial detachment of 50 mm or higher in this analysis (Table 1).

As presented by Oliveira et al [5] and previously used by Ghiassi [3] it is possible to estimate the slip profile knowing the strain distribution along the reinforcement at different instances, using the following:

$$\delta = \int \varepsilon(x)\, dx \tag{3}$$

With the slip profile obtained from the tests with strain gauges, it is possible to compare these results with the ones obtained with the video tracking acquisition. Table 2 shows the results obtained for the two different acquisition systems for the selected specimens. Regarding the maximum slip, the results are very similar with the exception of specimen I30 where the video equipment suggests almost the double of the maximum slip suggested by the strain gauges. Regarding the slip rate, the results are similar between both acquisitions.



a) b)

Figure 5: Examples of strain gauges signal acquisition: a) total detachment of the fabric; b) partial detachment of the fabric.

Table 2: Impact tests on GFRP-brick specimens.

	Strain Gauges			PHOTRON			
Specimen	**Max Slip (mm)**	**Slip rate (mm/ms)**	**Strain rate (/s)**	**Max Slip (mm)**	**Slip rate (mm/ms)**	**Force (kN)**	**DIF**
I41	0.31	0.10	2.6	0.32	0.07	14.97	1.62
I40	0.36	0.23	2.5	0.49	0.15	15.96	1.73
I46	0.86	0.70	3.7	0.84	0.74	17.15	1.86
I30	0.56	0.98	7.4	1.00	0.87	17.29	1.88

Adding these new results, obtained with strain gauges, to the results obtained with the video tracking acquisition (Figure 6) it is possible to see that these values fit perfectly in the range obtained with the video equipment, giving confidence in the obtained results.

A trendline was obtained for slip rates between 0.06 and 1.32 mm/ms (range of the performed tests). It was assumed that the trendline would start, with the same orientation, from a DIF value of 1.00. Is was also assumed that from the quasi-static slip rate until the point where the regime changes to dynamic, the DIF remains constant and equal to 1.00. Further testing for smaller slip rates is required to validate these assumptions.

The empirical relation that is able to translate the influence of the slip rate in the maximum force of these GFRP-brick, based on the obtained trendline, can be presented as Eq. (2), being the slip rate in mm/ms. This log-linear relation has an R^2 of 75%, which can be considered reasonable taking into consideration the nature of these materials and these tests. It is important to notice that considering only the results from the strain gauges, the obtained trendline would have a R^2 of 95%. Although the smaller sample size (4 values) does have an impact in this value, it seems that using strain gauges would improve the overall quality of the results. However, this technique increases considerably the costs involved in these experimental studies.

$$DIF(F_{MAX}) = \begin{cases} 1 & if \quad 2E \quad 5 < \delta < 2.71E \quad 3 \\ 0{,}1554\ln(\delta) + 1.9184 & if \quad 2.71E \quad 3 < \delta < 1.32 \end{cases} \tag{2}$$

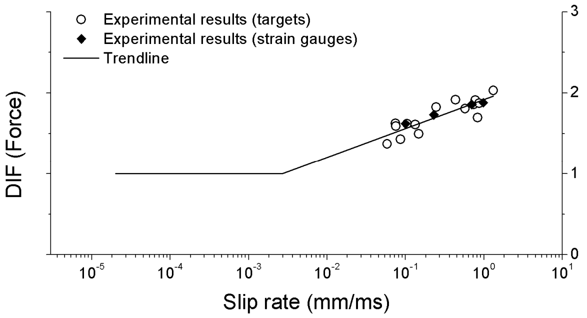


Figure 6: Dynamic increase factor for shear capacity of GFRP-brick at different slip rates.

Conclusions

From the obtained results it is clear that the slip rate influences the bond behaviour of these systems. These results show that for slip rates of around 1 mm/ms there is an increase of the maximum bond capacity of about two times the quasi-static value. These results, obtained with video tracking, were validated with strain gauges along the reinforcement in some of the tests. These tests with strain gauges also allowed determining the effective bond length, being the same as the obtained in quasi-static regime. Leading to conclude that the slip rate does not influence the effective bond length of these systems, similar to what has been observed by Al Zubaidy [6].

The log-linear empirical relation translating the influence of the slip rate on the DIF for the bond capacity of CFRP-Brick systems has been presented up to 1.32 mm/ms. This empirical relation was assumed to be constant and equal to one from the quasi-static slip rate until the intersection point with the trendline of the impulsive regime (2.7E-3 mm/ms). The failure modes obtained with these experimental tests under impulsive loading were characterized by the ripping of a thin layer of brick. These failure modes are similar to those obtained for quasi-static regime, leading to assume that the slip rate does not influences the failure mode of these systems, similar to the observed by Al-Zubaidy [6].

As shown in this work the slip rate or the strain rate (depending on what is measured) has considerable influence in the response of materials, including the bond behaviour of modern reinforcement techniques and materials such as GFRP. This influence has to be considered in the modelling and design of these systems under impulsive loading such as impacts or blast loading, and need to be incorporated in the constitutive models of these materials under non-linear analysis; similar to what has been done previously for masonry by Lourenço et al [27].

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