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Bond of GFRP Strips on Brickwork

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Abstract. Fiber reinforced polymers (FRP) have been increasingly popular over the past decades in civil engineering, even for the purpose of strengthening unreinforced brickwork. The primary aim of utilizing FRP on masonry walls is to enhance their strength-and displacements. To strengthen cross walls and increase tensile capacity during an earthquake, it may be convenient to use externally bonded (EB) Glass-FRP strips. This strengthening system is affected by loss of bond with delamination of GFRP strips from surface of bricks.
The investigation's findings regarding the bond between GFRP strips and modern brickwork masonry surfaces are presented in this paper. Pull-push shear tests were performed on brickwork specimens with different thickness of bed mortar joints strengthened by EB-GFRP strips. Failure's modes are described with shear-slip laws and energy fracture values.

Keywords: Glass Fibers, Delamination, Pull-push Shear Tests, Brickwork.

1 Introduction

In recent years, Fiber Reinforced Polymers (FRPs) have been increasingly used in the rehabilitation of buildings. In Italy, in particular, this success can be attributed to the presence of a historically and architecturally significant building heritage that requires preservation. Furthermore, it should be considered that a large amount of masonry buildings was damaged by earthquake that invested many areas of the Italian territory in the last years. From this point of view, a strong impulse towards structural consolidation is determined by the need to guarantee an adequate level of seismic safety.

FRPs have aroused considerable interest both in the field of reinforcement and in structural repair in seismic areas, as the application of these materials can make up for the lack of tensile strength of the walls and increase the deformation capacity, maintaining the parts connected, even in the presence of significant crack patterns, thus preventing brittle collapse mechanisms [1-5].

The use of these materials involves the introduction of new possible failure mechanisms which must be duly considered, such as, tensile failure of the fibres, compression failure of the masonry, loss of adhesion between the support and the composite [6,7]. The crisis due to detachment for loss of adhesion is of crucial importance for the effectiveness of strengthening; first, because maximum transfer of stress at the interface between the two materials can be reached only with complete adhesion and, secondly, because the loss of adhesion causes fragile failure.

In literature, numerous experimental research works point out the complexity of delamination phenomenon, analyzing the role of many factors that affect the bond behaviour in FRP-to-masonry bounded joints [6-11]. In addition, theoretical and numerical analysis [12-14] has been provided to predict the ultimate load, the effective bond length and the entire debonding propagation process in FRP-to-masonry bounded joints. It should also be added that in the specific case of application on masonry the phenomenon of adhesion is to be considered not yet sufficiently investigated [15], also due to the extreme variability of existing masonry types; furthermore, the role of the mortar joints is not yet perfectly clear, as they represent a geometric and mechanical discontinuity that could interrupt the effective adhesion area.

The study of brickwork strengthened by EB-GFRP strips may be influenced by non-homogeneous support with bricks and mortar layers. Furthermore, attention to delamination behavior should be focused also on the presence of an interface layer which is the adhesive layer between the GFRP and brickwork. The stresses that can lead to the collapse of the system are mostly concentrated in this area and for this reason the preparation of the interface layer and the gluing play a role of significant importance in the behavior of the GFRP strengthening. Collapse due to detachment between the support and the reinforcing fiber can occur in various ways: in the support material near the reinforced element; along the contact surface of the consolidated material and the adhesive; in contact between the thin layer of adhesive and the FRP; inside the FRP. Since the tensile and shear strengths of the adhesive are generally higher than those of the substrate, joint failure generally occurs in the substrate [7,8]. In this case, once the fracture has occurred, traces of the substrate remain attached to the reinforcing strip. If the fracture of the joint occurs between the support and the adhesive, or between the adhesive and the FRP strip, then the cause of the failure phenomenon could be traced back to poor preparation of the support and suboptimal bonding of the reinforcement. If FRP strengthening failure occurs, it is not induced by the mechanical properties of the joint and happens after the manifestation of a partial delamination of the strengthening itself.

This paper, through an experimental campaign, aims to study the phenomenon of debonding by considering brickwork trying to investigate what the role of mortar joints on bonding behavior. Pull-push shear tests were performed on brickwork specimens with EB GFRP strip with different bed mortar joints. Shear-slip laws of the specimens tested; energy fracture and failure load values were evaluated.

2 Experimental analysis

In this research work, bond tests were carried out on wallettes made with four courses of clay bricks and mortar layers. Six specimens were subjected to pull-push shear tests with different thickness of bed mortar layers. They were strengthened with a GFRP strip, placed in the normal direction respect bed mortar joints, subjected to tensile stress. In this way, the operating conditions of an existing masonry consolidated with EB FRP materials were reproduced.

A preliminary characterization of material was carried out before pull-push shear tests. To determine the compressive strength of brick, compressive tests were carried out on 6 samples measuring approximately 50x50x55mm on each side. A compressive strength of the brick equal to $f_{b,c}$=43.31N/mm^2 was obtained.

A hydraulic lime mortar was used to prepare the specimens. compression and bending tests were carried out to determine the mechanical parameters of mortar following the directives of the UNI EN 1015-11; 2001 standard. Flexural strength mortar was evaluated by three points bending tests on prismatic samples measuring 160x40x40mm until failure, while the compressive strength is determined on the two parts obtained from the flexural tests. An average compressive strength equal to $f_{m,c}$=12.15N/mm^2, and a tensile flexural strength equal to $f_{m,t}$=3.40N/mm^2 were obtained.

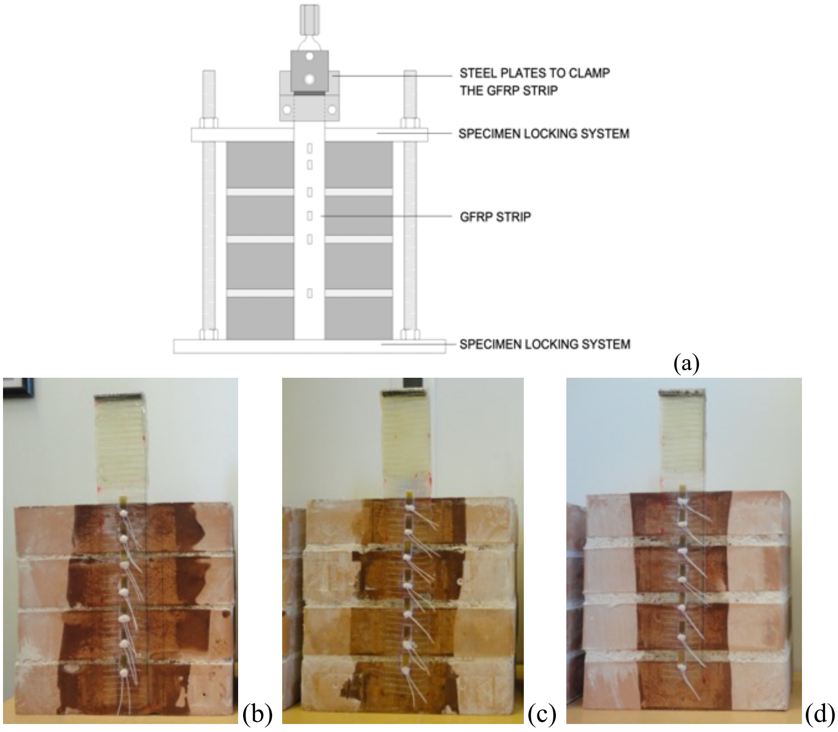
2.1 Specimens and set up of pull-push shear tests

The investigation involved three types of walls (W1, W2, W3), which differ in the thickness of the mortar joints. There are two specimens made for each type: W1-A,B with 4mm thick joints; W2-A,B with 8mm thick joints; W3-A,B: with 12mm thick joints. The compressive strength of the three types of walls were evaluated by uniaxial compression tests. The specimens subjected to uniaxial compression showed an average compressive strength equal to f_{cw}=13.93 N/mm^2.

GFRP strip was placed on the surface of wallettes perpendicularly to the mortar layers. The strip was characterized by a width of b_{GFRP}=50 mm and a thickness of about t_{GFRP}=1 mm. The GFRP used in this experiment is a unidirectional glass fiber fabric FIDGLASS UNIDIR 300 HS73 from the FIDIA company, characterized by a tensile strength equal to $f_{t,GFRP}$=1400N/mm^2 and a Young's modulus equal to E_{GFRP}=70000 N/mm^2.

The procedure for applying EB GFRP strips on the brickwork surface foresaw cleaning and smoothing the specimens' surfaces, applying a bi-component primer (type MBRACE PRIMER) to each one, and then gluing the GFRP strips together with epoxy resin (KIMITECH EP-IN). The epoxy resin had an average tensile strength equal to f_{res} = 30 N/mm^2 and Young’s modulus E_{res} = 1760 N/mm^2.

The instrumentation used in pull-out tests was made up of the testing machine and its set of anchoring devices specially adapted to the tested specimens (Fig. 1(a)), and the strain gauges. The tensile stress was applied only to the GFRP strip thanks to a specially created locking device, made up of plates and a system of bolts which hook onto the load cell at the top and hold the strip at the bottom. At the same time, the wall element was blocked through two metal plates, on the two faces perpendicular to the direction of traction; furthermore, the lower plate was firmly anchored to the support surface through clamps, to prevent any movement of the wall with respect to the fiber.



(a)

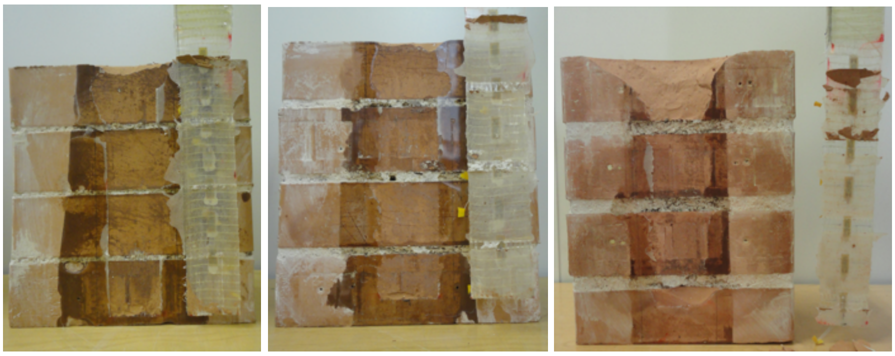
(b) (c) (d)

Fig. 1. Wallets with EB GFRP strips: (a) set up for pull–push shear tests; location of strain gauges and GFRP strip-to- brickwork joint for wallets with different thickness of mortar joints: (b) thickness h = 4 mm; (c) h = 8 mm and (d) h = 12 mm

During the positioning phase of the walls, particular attention was paid to guarantee the alignment between the point of load application and GFRP strip to maintain the tensile stress parallel to the faces of the wall and not create twisting actions on fiber. Using this equipment, a perfect fixing of the specimen was obtained; thus, the wall system was made neutral in relation to the dynamics at the resin interface. In this way, the quality of the deformations measured by the strain gauges was guaranteed. As previously mentioned, strain monitoring was performed using seven strain gauges glued to the upper surface of the GFRP strip. Figs. 1(b)-(d) shows the arrangement of the strain gauges for each type of wall. The number of strain gauges applied on each specimen is the same, but due to the different thickness of the mortar joints, the distances between them are different.

2.2 Results of pull-push shear tests

During the pull-push texts the GFRP strips reached detachment by delamination; in some cases, it was accompanied by collapse of GFRP under tensile stress. The delamination failure of brickwork wallettes is shown in Fig. 2. It is possible to notice that delamination of the GFRP strip did not cause the detachment of the surface layer of the support element.

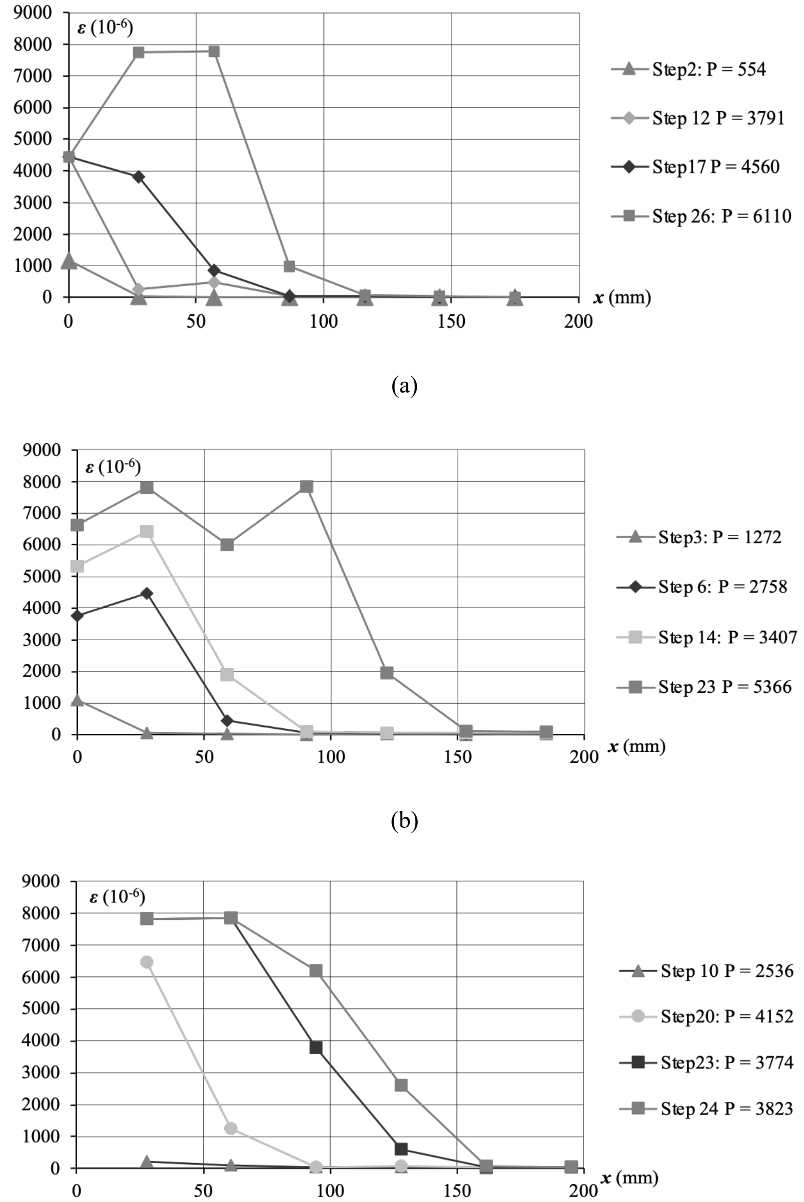


(a) (b) (c)

Fig. 2. Delamination failure of GFRP strip-to- brickwork joint for wallets with different thickness of mortar joints: (a) thickness h = 4 mm; (b) h = 8 mm and (c) h = 12 mm.

The W1 specimens, with 4mm thick mortar joints, showed a failure in the pull-out test with the complete detachment of the reinforcement strip at a maximum load, respectively, of 6298N and 7903N. In the case of specimens with 8mm thick mortar joints, the W2-A specimen failed with the complete detachment of the reinforcement strip for a load equal to 6296N. For W2-B specimen, the failure in the pull-out test occurred with a partial detachment of the reinforcing strip from the support and a subsequent fracture of the fiber between the strain gauge number seven and number six (Fig. 2(b)). The collapse occurred when the maximum load of 7273N was applied. For W3-A specimen, with a joint thickness of 12 mm, the failure occurred due to the partial detachment of the reinforcing strip from the wall and the subsequent fracture of the GFRP strip. Complete failure occurred at the maximum load of 7345N. For specimen W3-B, the failure in the pull-out test was reached with a total detachment of the reinforcing strip from the wall at a maximum load of 6221N. Therefore, it is easy to confirm that there was no discernible difference between the three types of wallets Wi with i = 1,...,3 because the values for the failure loads were quite similar.

As already described, the evolution of strains along the GFRP strip was traced during pull-push tests until failure of joints. Fig. 3 shows the diagrams of strain values along the GFRP recorded during pull-push shear tests. The point when delamination started can be captured by analyzing the experimental diagrams of strain vs length of GFRP strip. In fact, it is possible to notice that the loss of bond and, consequently, the detachment of GFRP strip from the masonry support started at the point where we see a changing in the slope of diagram and continued until the complete detachment of the GFRP strengthening or its tensile failure. The wallettes exhibited a maximum strain valued equal to about $\varepsilon = 8 \cdot 10^{-3}$; no relevant different between specimens was noticed.



(c)

Fig. 3. Strain values recorded during pull-push tests (a) W1-A, (b) W2-A and (c) W3-B.

3 Discussion

The delamination of GFRP strip glued on brickwork was evaluated recording strain values with a number m of strain gauges.

The method used to define slips is described below [8,16]; starting from the last strain gauge placed at $x = x_m$, gives us the expression of displacement at the generic abscissa x, with $x_i \leq x \leq x_{i+1}$ (Fig. 4):

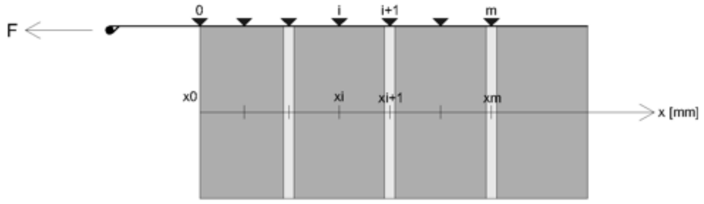


Fig. 4. Pull-push setup for GFRP–brickwork masonry delamination test.

$$\delta(x) = \delta(x_{i+1}) + \int_x^{x_{i+1}} \varepsilon(\zeta)\mathrm{d}\zeta = \tag{1}$$

$$= \delta(x_{i+1}) - \frac{1}{2}\left(\frac{\varepsilon_i - \varepsilon_{i+1}}{x_i - x_{i+1}}\right) \cdot (x_{i+1} - x)^2 + \varepsilon_i(x_{i+1} - x)$$

The value of $\delta(x) = 0$ is assumed at strain gauge x_m.The average slips between two successive strain gauges are evaluated with:

$$\delta_{i+1/2} = \frac{\delta(x_{i+1}) + \delta(x_i)}{2} \tag{2}$$

Finally, for a given load level P, the average value of the interface tangential stress between two successive strain gauges is obtained by adopting the equation shown below:

$$\hat{\tau}_{i+1/2} = \frac{E_{\mathrm{GFRP}} A_{\mathrm{GFRP}} (\varepsilon_{i+1} - \varepsilon_i)}{b_{\mathrm{GFRP}} (x_{i+1} - x_i)} \tag{3}$$

where A_{GFRP} is the transversal area of GFRP.

Fig. 5 shows the diagrams representing the trend of the slips as a function of the tangential interface stresses for the most significant load steps for the three types of specimens.

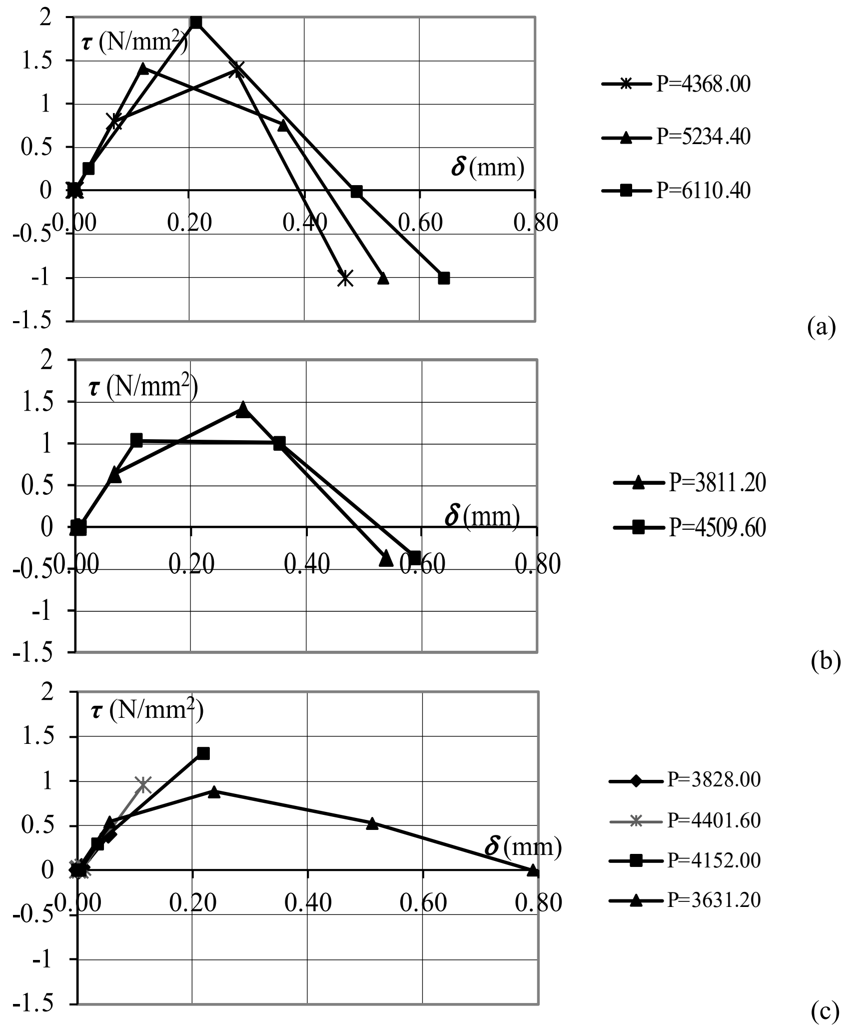


Fig. 6. Experimental shear stress–slip laws for specimens: (a) W1A; (b) W2A; (c) W3B.

Attention is now focused on fracture energy of the interface law, that is the energy per unit of surface area necessary to locally break the adhesion bond. The evaluation was carried out by calculating the area subtended by the curve that links the tangential interface tensions to the slip (τ-δ). Average values of fracture energy G_f obtained experimentally for each kind of specimens in relation to different mortar joints thickness are given in Tab. 1. Starting from experimental fracture energy values and using the formula [7], based on the hypothesis of a simplified linear model, the maximum load was evaluated, as it follows:

$$P_1 = b_{GFRP} \cdot \sqrt{2 \cdot E_{GFRP} \cdot t_{GFRP} \cdot G_f} \quad (3)$$

Tab. 1 summarizes the average results obtained from delamination tests, in terms of maximum delamination load, slips, tangential stresses and fracture energy; furthermore, a comparison is provided between the maximum delamination load evaluated analytically and that obtained experimentally.

Table 1. Experimental ultimate average loads and fracture energy by pull–push test and theoretical average ultimate load.

	Thickness of mortar joints [mm]	**Exp. average ultimate load** $P_{max,av}$ [N]	**Average slip** $\delta_{f,av}$ [mm]	**Average tangential stress** $\tau_{f,av}$ [N]	**Exp. average delamination load** $P_{del,av}$* [N]	**Exp. average fracture energy** $G_{f,exp}$ [N/mm]	**Theor. average delamination load** P_I [N/mm]
W1	4 mm	7101	0.182	2.21	5960	0.51	4637
W2	8 mm	6785	0.171	1.80	5997	0.40	4103
W3	12 mm	6783	0.205	1.93	5621	0.51	4613

*$P_{del,\,av}$= maximum delamination load (corresponds to the collapse of the fourth strain gauge).

Remembering that specimens W1, W2 and W3 have mortar thicknesses of 4mm, 8mm and 12mm, we can note that the ultimate load, P_{max}, which leads to the failure of specimen is almost the same for all specimens. The same consideration can be made for fracture energy values. By comparing the theoretical delamination load P_I with the one obtained experimentally it can be observed that the theoretical values are lesser than the experimental values so that, although theoretical value of delamination load has been obtained assuming a linear elastic behaviour, the theoretical value may be considered safe in practice.

4 Conclusion

In this paper an experimental analysis was presented to investigate the delamination failure of GFRP strips externally bounded on brickwork masonry. The aim is to evaluate the difference in delamination behavior of GFRP applied to masonry elements with different thicknesses of mortar joints, trying to understand how the latter can influence the detachment process of reinforcement from support.

The primary findings of this research can be summarized as follows:

- The delamination behavior remains unaffected by variations in the thickness of bed mortar layers.
- Delamination failure can be attributed to a relatively low fracture energy value, which ranges between 0.40 to 0.51 N/mm.
- As the thickness of the joints varies, the specimens show comparable values of tangential stresses and slips. The GFRP to-brickwork masonry bonded joints exhibited a maximum ultimate shear stress τ_f~2.21 N/mm^2 when the mortar thickness was 4 mm. The maximum recorded slip values δ_f reached

0.205 mm for GFRP to-brickwork masonry bonded joints with a mortar thickness of 12 mm.

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