Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1553

OPTIMUM PATTERN OF FRP FOR STRENGTHENING MASONRY WALLS

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ABSTRACT

One of the techniques for retrofitting masonry structures utilizes fiber reinforced polymer (FRP). Because masonry walls may have different modes of failure, their retrofitting must be in accordance with their failure mode. Because of its high tensile strength and low weight FRP is an effective material for retrofit projects. It is crucial in the design of retrofitted structures to be able to model the behavior of masonry and FRP accurately. In this study Diana9.3, a software capable of modeling nonlinear behavior of masonry is used for modeling the walls. This article, after verification of the model, used for masonry walls with different failure modes and FRP describes the suitable patterns that have been determined for each situation on hand.
Keywords: masonry wall, failure mode, retrofit, FRP

Introduction

Existing unreinforced masonry (URM) buildings constitute a significant portion of historical buildings around the world. It is well known, however, that such buildings are vulnerable to earthquake motion. For this reason retrofitting of these structures are under way in many countries.

Several conventional techniques (shotcrete, grout injection, …) are available for retrofitting of seismically inadequate URM buildings. The disadvantages of these techniques include lengthy construction time, reduced available space, disturbance to the occupants and changes to the aesthetics of the existing buildings. In addition, the added mass can increase the earthquake induced inertia forces that my in turn require strengthening of the foundation. Most of these problems can be ameliorated by using fiber reinforced polymers. FRPs may include different types of fibers; glass (GFRP), carbon (CFRP) or aramid (AFRP). An important factor influencing the behavior of URM-FRP is the retrofitting configuration. Schwegler is one of the investigators who have studied such configurations. He found that the best retrofitting configuration includes the use of inclined FRP strips and full surface coverage (Schwegler 1994). Zhao et al. also show that diagonal plates of CFRP significantly improve the lateral resistance of uncracked specimens (Zhao et al. 2003). Elgawady et al. have investigated the effectiveness of externally bonded FRPs as retrofitting materials for the in-plane strength of URM walls (Elgawady et al. 2004). They found that specimens retrofitted with full surface coverage GFRPs have lateral resistances up to 1.5 times

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the lateral resistance of a reference specimen. However, after GFRP ruptures the specimen behaves in the same manner as the reference specimen.

Because of the complexity of the behavior of masonry, it is necessary to use a software that allows correct modeling of this behavior. There are a number of softwares such as Adina, Diana,… that allow modeling of nonlinear behavior of masonry structures (Diana 2008). In this article Diana 9.3 is used for modeling purposes. In addition masonry walls may have different failure modes that the retrofitting process must consider. In this article the result of a study using walls with different failure modes retrofitted by a variety of FRP patterns are presented. The most suitable pattern for each failure mode is then identified.

Properties of masonry walls investigated

The nonlinear behavior of masonry walls used in this study is modeled by finite elements. The heterogeneity of the masonry material resulting from the composition of blocks and mortar can be modeled in two different ways; Macro or Micro modeling. Micro modeling was used in this study because it provided more detailed information. Micro models are the best tools available understanding the behavior of masonry. The benefit of such models is that they depict all the failure mechanisms of the system.

In the socalled simplified micro-models, larger masonry units are represented by continuum elements. The behavior of the mortar joints and masonry unit-mortar interface is lumped in a set of discontinuous elements. In this way each joint, consisting of mortar and the two unit-mortar interfaces, is modeled by a zero-thickness interface element. The unit dimensions are augmented in order to keep the geometry unchanged. Masonry is thus modeled by a set of elastic blocks bonded together with potential fracture/slip lines at the joints (Lourenco 1997).
The elastic stiffness of the interface layer is determined from the following equations:

$$k_n = \frac{E_b E_m}{h_m (E_b - E_m)} \qquad k_s = \frac{G_b G_m}{h_m (G_b - G_m)} \qquad (1)$$

Here E_U and E_m are Young's moduli, G_U and G_m shear moduli of the masonry unit and mortar, and h_m is the actual thickness of the joint.

A composite interface model, which includes a tension cut-off for mode I failure, a coulomb friction envelope for mode II failure and a cap mode for compressive failure, which has been developed from plasticity concepts, in used to model the material, Figure 1. In addition, interface elements are used for modeling potential cracks in the units. The assumption that all the inelastic behavior occurs in the interface elements, leads to a robust type of modeling, capable of determining the complete load-deformation path of a structure until total degradation of stiffness occurs.

The description of the material in the nonlinear range requires that the softening part of the material behavior be included in description of the material model. The parameters necessary for the depiction of the nonlinear behavior of the model are, the tensile strength of the joint (f_t), mode I fracture energy of the joint (G_f^I), cohesion of the joint (C), mode II fracture energy of the joint

(G_f^{II}), measures of the friction and dilatancy of the joint ($\tan\phi$, $\tan\Psi$), The latter is equal to the uplift of one unit over the next one, upon shearing, and the compressive strength of masonry (f_m).

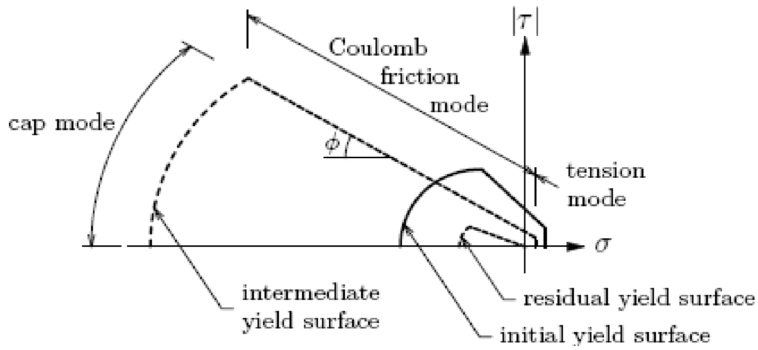


Figure 1: Interface model for masonry

It should be noted that the fracture energy is the area under the stress-crack displacement diagram in a direct tension test. This is a measure of the amount of energy necessary to open a crack of unitary area. A similar definition is used for shear and compressive behavior. Van der pluijm has conducted deformation controlled tests on small masonry specimens of solid clay and calcium-silicate units. These tests have resulted in an exponential tension softening curve with a mode I fracture energy G_f^I ranging from 0.005 to 0.02 [Nmm/mm^2], for a tensile bond strength the results range from 0.3 to 0.9 [N/mm2], for the masonry unit-mortar combination. Mode II fracture energy (G_f^{II}), have values from 0.01 to 0.25[Nmm/mm^2] for values of initial cohesion (C) from 0.1 to 1.8 [N/mm^2]. The tensile strength were determined by direct tension tests, with cohesion (C) equal to $1.5f_t$.

For the numerical analyses masonry units are represented by 8 node plane stress elements, while the joints are represented by 6-node interface elements. The latter elements are also provided in the middle of masonry unit in order to predict vertical cracks.

Properties of FRP

Polymer-matrix composites are much stronger in the fiber direction than in the other directions. Tensile failure in the fibre direction is controlled by the fibre strength, while tensile strength perpendicular to the fibres is controlled by the strength of the matrix and the bond between the fibre and the matrix. FRP can be modeled by one of the following elements:

a. Shell element: The thickness of curved shell elements can subdivided into a number of layers representing the layers of FRP. Each layer can be given its own material properties and material direction. Such an orthotropic material can be modeled with orthotropic material model with the Hoffmann failure criterion. In order to avoid shear locking a 2x2 Gaussian integration scheme is used. A 3-point Simpsons rule integration is used for this element. The Hoffmann criterion is a modification of the criterion proposed by Hill, with the equality of tensile and compressive yield strengths removed.

b. Truss element: For truss/cable elements a 2-point Gaussian integration scheme is used for the calculation of the axial strains and stresses. A uniaxial nonlinear elasticity model, with appropriate elastic moduli and stress limits is used for cable elements to model the CFRP. In a few cases convergence could not be achieved using layered curved shell elements.

Verification of wall and FRP model

For the verification of FRP models an experiment by Milani is used, which provides most of the parameters necessary for the characterization of the material in the numerical model. The experimental study is conducted on horizontal strip of CFRP applied on a masonry panel. A uniaxial compressive load is applied at the middle of the wall that fails in bending (Milani 2006). A comparison between experimental observation and numerical results shows good agreement, Figure 2.

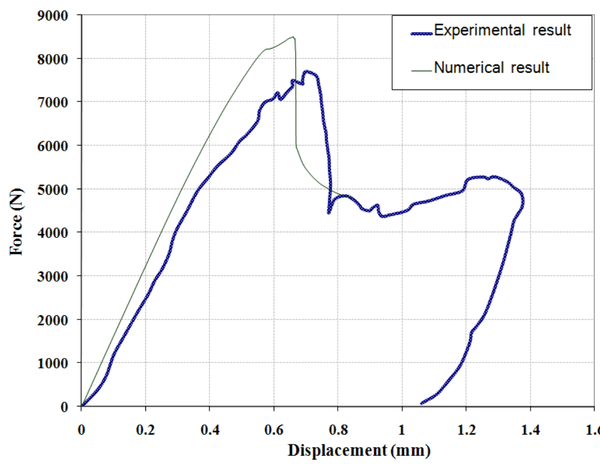


Figure 2: Comparison load-displacement curve of the experimental and numerical results for masonry wall

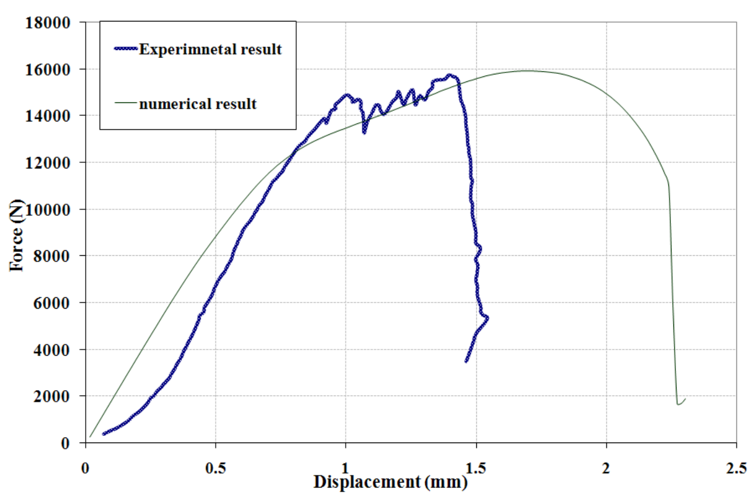


Figure 3: Comparison load-displacement curve of the experimental and numerical results for wall strengthened with frp

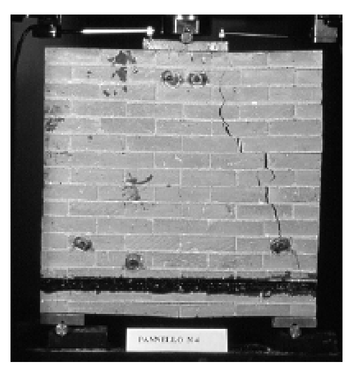


Figure 4: Experimental crack pattern

If the delamination phenomenon of the FRP from the wall is not considered, failure occurs at high values of displacement, Figure 3. Also, based on the experimental and numerical results, two diagonal cracks start at the support and spread in the direction of the applied load, Figure 4.

Retrofitting walls with FRP

Since masonry walls have different failure modes, the failure mode must be considered in retrofitting procces. Thus, in the first step in retrofitting is the determination of the failure mode. Subsequently the different FRP patterns for that mode are determined and the most suitable one is selected.

FRP patterns for walls with rocking mode

In this section masonry walls are selected such that their failure mode is rocking. The dimensions of the wall, are 3×3 m. They are cantilever, fixed at their base. Initially, the walls are subjected to a vertical load 32.57 KN/m2 , uniformly distributed over the length of the wall. After imposing the vertical force F on the top of the wall a horizontal displacement d is effected. The boundary conditions and applied loads are similar in all cases.

The strengthened configurations with FRP are:

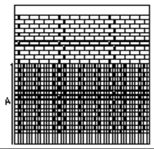
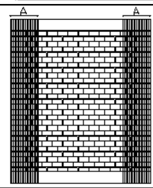
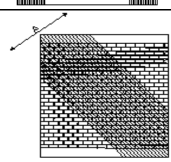
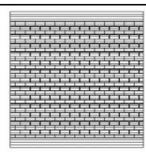
1. FRP in vertical direction, starting from the base of the wall.
2. FRP at both ends in vertical directions.
3. FRP in diagonal direction.
4. The whole surface of the wall covered with FRP with fibers in the horizontal direction.

The various failure modes and capacities are given in Table 1.

With fibers in the vertical direction over 50, 75 cm and 1 m distance from the base, The variation in capacity was negligible. In these cases the rocking mode is simply transferred to the top end of the FRP. But when the wall is strengthened for a 2 meter depth, the increase in capacity is considerable. This result becomes obvious when we notice that, because the wall is reinforced over a 2 meter distance. The unreinforced or vulnerable part is 1 meter in depth. When the two ends of the wall are strengthened in the vertical direction, the variation in the FRP width has no effect on the capacity of the wall. The FRP in the tensile portion of wall prevents the rocking mode of the wall. The wall mode of failure changes to sliding bed joint. In this way, the FRP element in the middle portion of the wall has no effect on the capacity of wall, because it is in the neutral portion of the wall.

The FRP placed in diagonal direction has the most effect on the capacity of wall ,Figure 5, as it is directly subjected to tension. The increase in the capacity is related to the width of the FRP strip. In all cases of strengthening in the diagonal direction the failure mode is rocking, Figure 6.

Table 1: Retrofit patterns of FRP for walls with rocking mode

Strengthening	Width or distance	Failure mode	Increasing capacity
	0.5, 0.75 and 1 m	rocking	1.2
	2 m	Rocking-sliding	2.1
	Full surface	sliding	2.7
	22.5,45 and 67.5 cm	sliding	2.5
	0.25,0.5,1,2 and full surface	rocking	1.9, 2.4, 3.3, 4.15 and 4.2
	Full surface in horizontal	rocking	1.1

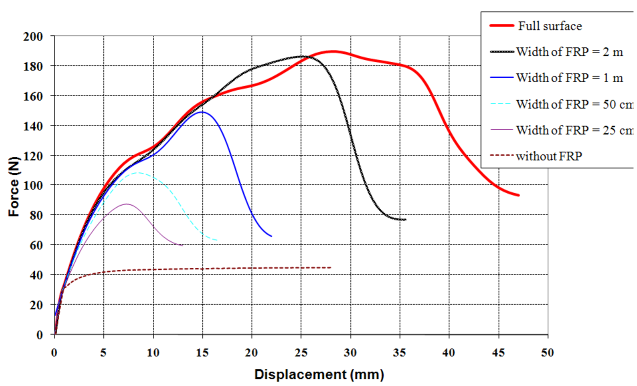


Figure 5: load-displacement for Strengthening wall in diagonal direction

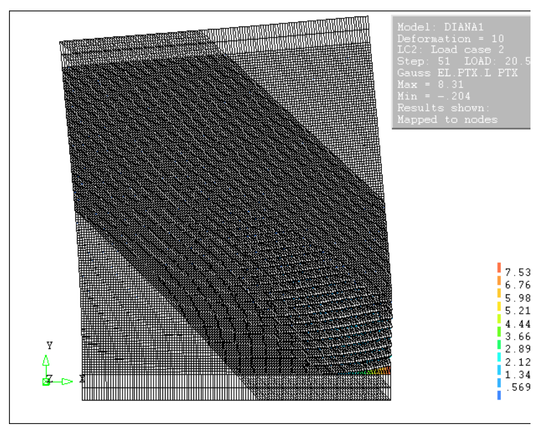


Figure 6: crack pattern in wall strengthened in the diagonal direction-width of FRP = 2 m

When the whole face of the wall is strengthened in the horizontal direction, tensile cracks in cannot open in the head joints. Therefore, this strengthening pattern is unable to prevent the rocking mode. Consequently, in walls with rocking mode, strengthening configuration at two ends in the vertical direction and in diagonal direction are preferable.

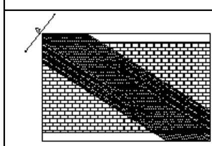
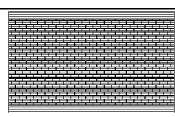
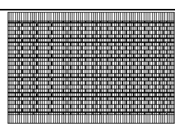
Appropriate patterns of FRP for walls with sliding bed joint

For this portion of the study, the walls are selected in such a manner that their failure mode is sliding bed joint. The dimensions of the walls are 5×2.7 m. A uniform precompression distributed forces of 0.3 N/mm2 is applied at the top of the wall, before a monotonically increasing load is applied in the the form d displacement control protocol. The strengthening configurations with FRP consist of three cases:

1. Retrofitting the wall in the diagonal direction
2. Covering the whole surface of the wall with FRP with fibers in the horizontal direction
3. Full surface coverage in the vertical direction

The failure modes and capacity in these cases are given in Table 2.

Table 2. FRP patterns for walls with sliding bed joint mode

Strengthening	Width or distance	Failure mode	Increasing capacity
	33, 65 and 130 cm	sliding	1.25, 1.64 and 1.92
	2.5 m and full surface	rocking	3.22 and 4
	Full surface in horizontal direction	Sliding	1.1
	Full surface in vertical direction	sliding	1.1

The use of an FRP strip in the diagonal direction has the most effect on the capacity of the wall. The increase in the capacity is related to the width of FRP. When the full surface of the wall in retrofitted with FRP in the horizontal direction the failure mode is sliding bed joint and the increase in the capacity is negligible, Figure 7. In this case, the FRP prevents the head joints from opening. Therefore such a strengthening configuration is not capable of preventing sliding bed joint mode, Figure 8. When the full surface of the wall is strengthened in the vertical direction, the failure mode is sliding bed joint, as well. Here again the increase in the capacity is negligible, because FRP has a low shear strength.

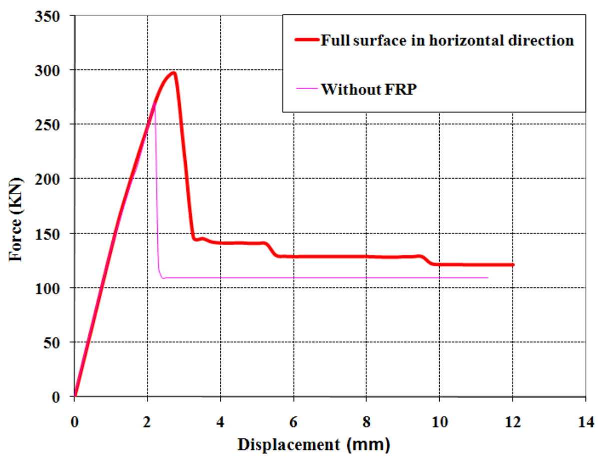


Figure 7: Load-displacement for Full surface strengthening wall in horizontal direction

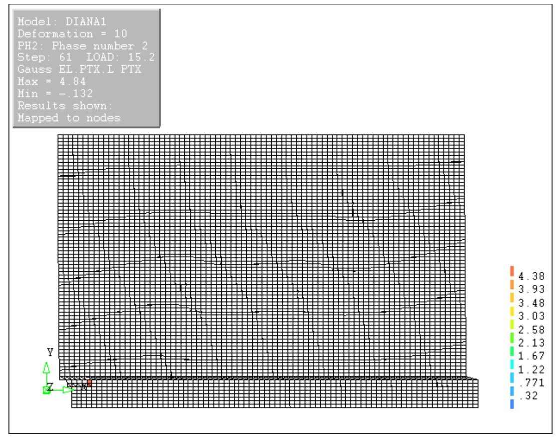


Figure 8: Crack pattern for Full surface strengthening wall in horizontal direction

The conclusion is that in walls with sliding bed joint mode, strengthening in the diagonal direction is preferred. While in full surface strengthening of the wall in the vertical and horizontal directions, the increase in capacity is negligible.

FRP patterns for walls with diagonal tension failure mode

Again the masonry wall is selected such that the failure mode is diagonal tension. The wall dimensions are 3×3 m. A uniform vertical precompression force of 0.3 N/mm2 is applied to the wall. A horizontal load is then monotonically increased in displacement control manner in a confined way that is keeping the bottom and top boundaries horizontal and precluding any vertical movement.The strengthening configurations with FRP consist of three cases:

1. Strengthening in the diagonal direction
2. Full surface strengthening with fibers in the horizontal direction
3. Full surface strengthening with fibers in the vertical direction

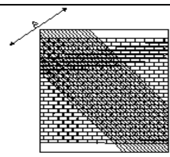
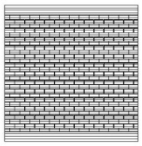
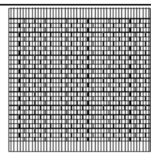
The failure modes and capacities in these cases are shown in Table 3.

When strengthening the wall in the diagonal direction with 25, 50 cm width FRP strips, the increased capacity is negligible, because the failure mode changes from diagonal tension to sliding bed joint. Such change is not suitable, because of the low shear strength of the mortar and small width.

On the other hand, when strengthening the wall with larger FRP widths, the failure mode changes from diagonal tension to rocking. Because of this change, the capacity is increased substantially.

Strengthening of the wall by covering its whole surface with FRP fibers in the horizontal direction cause a change of failure mode from diagonal tension to sliding bed joint. Here again the increase in the capacity is negligible. In this case FRP elements prevent the opening of tensile cracks in the head joints.

Table 3. Investigation various patterns for wall with diagonal tension mode

Strengthening	Width or distance	Failure mode	Increasing capacity
	25, 50 cm	sliding	1.02 and 1.06
	1,2 m and full surface	Rocking	1.36, 2.13 and 2.4
	Full surfaces in horizontal direction	Sliding	1.1
	Full surfaces in vertical direction	Diagonal tension	1.1

Covering the full surface of the wall with FRP fibers in the vertical direction, cause a negligible increase in the capacity, Figure 9. The failure mode is diagonal tension, Figure 10.

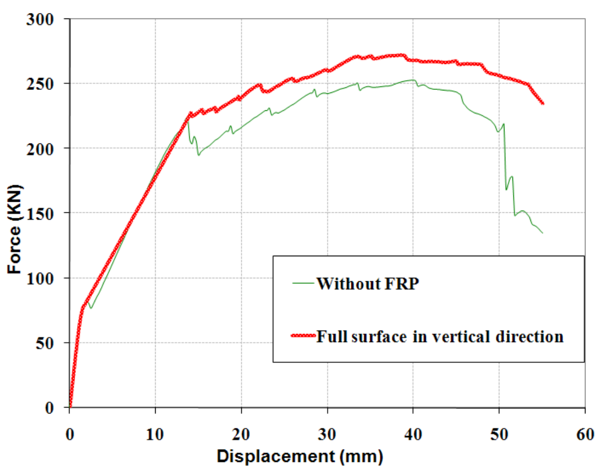


Figure 9: Load-displacement for Full surface strengthening wall in vertical direction

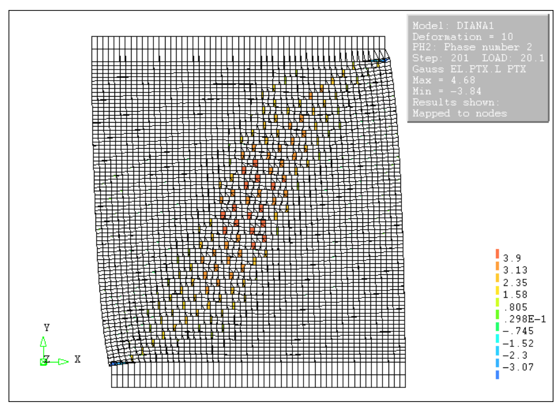


Figure 10: Crack pattern for Full surface strengthening wall in vertical direction

In walls with diagonal tension mode of failure, strengthening in the diagonal direction is preferred. But in full surface strengthening of the wall with the FRP fibers in vertical and horizontal directions, the increase in capacity is negligible.

Conclusions

In this study various wall configurations were retrofitted with a variety of FRP patterns.The walls, subjected to displacement controlled loading protocol were analyzed by the computer program Diana. The following conclusion can be drown from the results.

The retrofitting of the wall should be based on its failure mode. In walls with rocking mode, the best strengthening configuration is diagonal. Also in walls with sliding bed joint and diagonal tension failure modes strengthening in the diagonal direction is appropriate. In full surface strengthening of the wall with FRP fibers in the horizontal direction, the increased capacity is negligible.

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