FRP Strengthening and Repair of Unreinforced Brick Masonry Walls

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ABSTACT

Unreinforced masonry (URM) structures comprise a considerable proportion of the building stock worldwide. However, these structures generally do not behave well under extreme wind or earthquake loading. As part of on-going research, the behavior of these structures along with methods to retrofit them using fiber-reinforced polymers (FRP) is being investigated. Retrofitting methods using FRP include externally bonded (EB) sheets or pultruded plates/strips, and near surface mounted (NSM) strips or rods/bars. The fundamental failure mechanisms are being identified and investigated through experimental and analytical research. Since the material properties of concrete and masonry are similar, some research related to FRP retrofitted reinforced concrete (RC) is transferable to FRP retrofitted URM. However, many characteristics are also unique to URM structures. This paper presents a brief overview of the state-of-the-art of unreinforced modern clay brick masonry walls retrofitted with vertically oriented FRP subject to out-of-plane and in-plane loading.

Keywords: Fiber-reinforced polymer, out-of-plane, in-plane, externally bonded, near-surface mounted, unreinforced brick masonry

INTRODUCTION

Many existing unreinforced masonry (URM) structures around the world are vulnerable to failure due to out-of-plane and in-plane loading from extreme wind or earthquakes. Due to several failures of masonry structures during earthquake events (e.g. Newcastle, Australia in 1989 and Kocaeli, Turkey in 1999) the development of new techniques for strengthening or repairing masonry structures is in high demand.

Many of these strengthening techniques include the use of fiber-reinforced polymers (FRP) in the form of sheets, strips, bars, or plates. FRP materials are gaining acceptance to strengthen URM structures in large part due to their durability, light weight, and general ease of application.

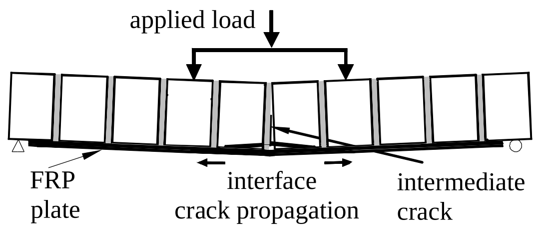
Early applications of FRP strengthening of masonry walls were by the wet lay-up technique with unidirectional or bi-directional fiber orientations depending on the type of loading and boundary conditions. This technique is generally applied over the entire face of the wall, or in wide strips. Although very efficient in increasing strength, or more importantly, deformation capacity, it is only a viable option when aesthetics are of no concern. So, unless the FRP sheets are covered by an external facade, this approach is not acceptable for historical or heritage listed structures. In a similar approach the external bonding (EB) of pultruded FRP plates has also been shown to be effective [1]. In all EB applications, surface preparation is critical to ensure a good bond at the critical adhesive-masonry interface. Experimental tests have shown that excessive effort may in fact damage the brick surface and compromise the integrity of the interface. A careful balance must be reached. EB systems are typically anchored at the ends to prevent premature debonding using a variety of methods.

A more recent technique is to bond the FRP in a groove cut into the masonry in a technique commonly referred to as near-surface mounting (NSM) [2]. The NSM technique typically uses round/square bars or narrow strips. NSM FRP may be placed in the vertical and/or horizontal direction depending on the loading and boundary conditions of the wall. Unlike EB, the NSM technique has minimal impact on the aesthetics of the masonry facade. Further, when narrow strips are used less construction effort is required as the groove may be made with a single saw-cut, the resistance to various forms of debonding is improved, and the FRP is better protected from environmental effects and intentional damage.

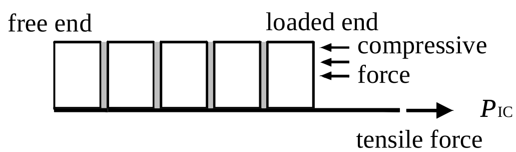
FUNDAMENTAL BEHAVIOR OF BONDED FRP-TO-MASONRY JOINTS

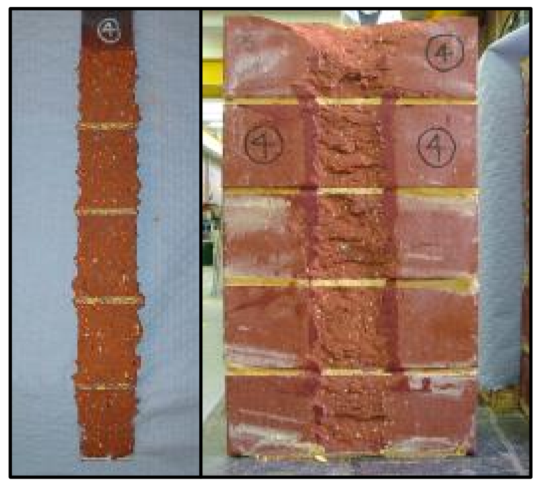
As in the FRP flexural strengthening or repair of reinforced concrete (RC) members, for example [3, 4], the most critical debonding mechanism is intermediate crack (IC) debonding. As illustrated schematically in Fig. 1a, interface debonding cracks develop and propagate along the adhesive-masonry interface originating from the discontinuity at the location of a flexural crack in the masonry. The tensile stresses developed in the FRP are transferred through shear to the masonry and as the flexural cracks widen with increasing applied load, the interface cracks join and propagate towards the plate ends at which time the strain in the FRP decreases as the FRP detaches from the masonry and IC debonding is said to occur. IC debonding is considered a critical mechanism because it governs the increase in the moment capacity and the ductility of the strengthened section.

Simple push-pull tests as shown in Figs 1b and 2 are typically used to simulate the IC debonding mechanism. The test involves subjecting the FRP bonded to a masonry prism to a direct tensile force. From a push-pull test, the fundamental interface shear stress-slip behavior of the FRP-to-masonry joint can be determined, which is analogous to a material constitutive model. Fig. 2a simulates a vertically oriented FRP strip (that is, perpendicular to bed joints) and Fig. 2b a horizontally oriented FRP strip (that is, parallel to bed joints). The test set-up shown in Fig. 2b also illustrates the application of transverse precompression representing the self-weight of the wall, or other vertical applied loads, and has been shown to improve the bond resistance of horizontally oriented NSM strips [5].



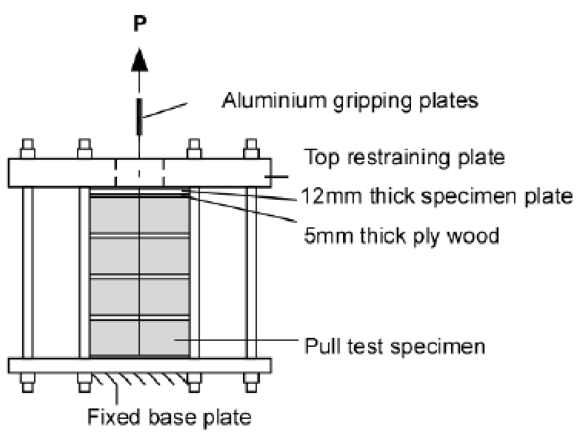
(a) IC debonding in bending beam test

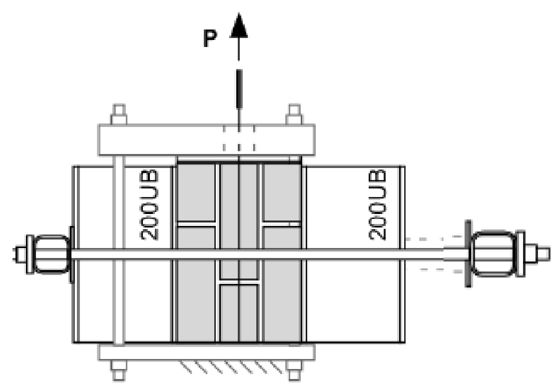




(b) Idealized IC debonding mechanism (c) IC debonding of EB plate

Figure 1. Intermediate Crack (IC) debonding mechanism





(a) vertically oriented FRP strips (b) horizontally oriented FRP strips

Figure 2. Typical push-pull test set-up

Push-pull tests are also used to experimentally determine the effective length of adhesively bonded FRP-to-masonry joints, which is the minimum length required to achieve the maximum IC debonding resistance. It has also been demonstrated that push-pull tests provide a lower bound to the IC debonding resistance in flexural members [3].

This is due to the combination of the interaction of interface shear stresses at the bonded interface between flexural cracks, and the curvature.

The interface shear stress-slip relationship (herein referred to simply as bond-slip) is easily determined experimentally from push-pull tests using strain gauges measuring the FRP axial strain distribution along the bonded length [2]. The typical bond-slip model is idealized as a bi-linear curve as shown by the dashed line in Fig. 3. The bond-slip relationship is used in the development of analytical models describing the complete behavior of such adhesively bonded joints [6], and in the definition of interface elements in numerical models [7].

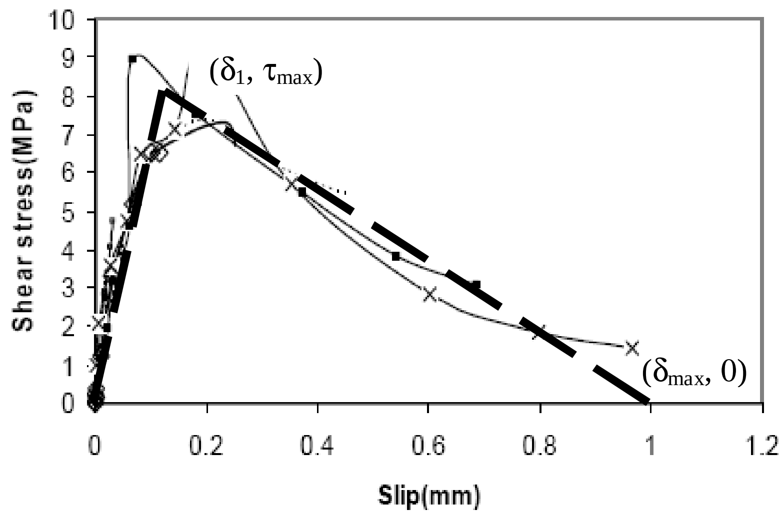


Figure 3. Typical bond-slip relationship of adhesively bonded FRP-to-masonry joints

In Fig. 3 there is an initial elastic region until the maximum shear stress τ_{max} is reached at slip δ_1, which is followed by a softening region up to slip δ_{max}, where interface microcracking is developing. Beyond δ_{max}, visible macrocracks form representing the debonding region. The bi-linear nature of the bond-slip curve gives the effective length, beyond which there is no further increase in IC debonding resistance. This is fundamentally different than internal steel reinforcement, where the anchorage length may be increased until yielding of the steel using the material to its full capacity.

It has been shown that the IC debonding resistance is given by the following fundamental expression [8]

$$P_{IC} = \sqrt{t_{\max} d_{\max}} \sqrt{L_{per} (EA)_p} \quad (1)$$

where $\tau_{max}\delta_{max}$ is equivalent to twice the fracture energy, which is the area under the bond-slip relationship shown in Fig. 3, L_{per} is the length of the debonding failure plane surrounding the plate cross-section as defined by the dashed lines in Fig. 4, and $(EA)_p$ is the axial rigidity of the FRP plate. The uniqueness of Eq. 1 is that it is presented for the first time in a form that unifies EB and NSM techniques in one formulation.

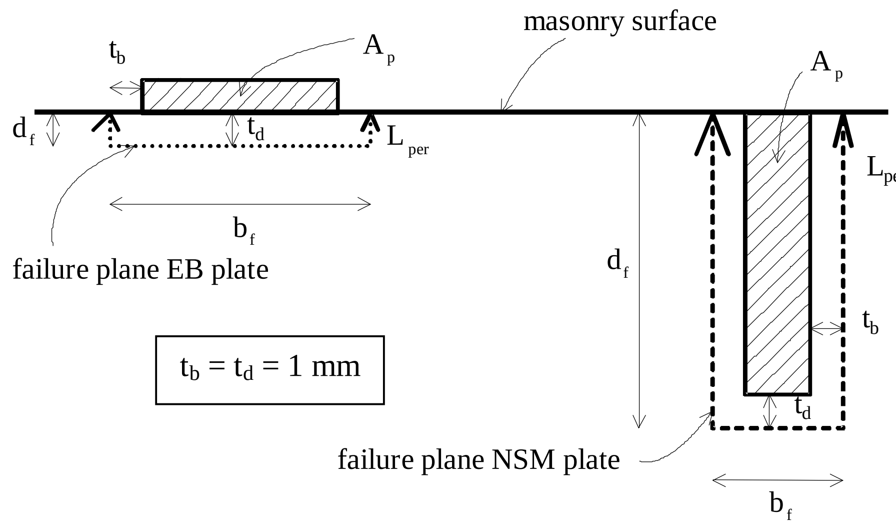


Figure 4. Definition of IC debonding failure plane (cross-section shown)

To-date, several push-pull tests have been published in the open literature [9, 10] investigating various modern clay brick units (including solid and cored), mortar properties, orientation of FRP relative to bed joints, effect of precompression (for horizontally oriented NSM strips only), location of FRP relative to cores, mortar joints and edges, and bonding technique (including EB pultruded plates and NSM strips).

The improved efficiency of NSM strips compared with the EB technique can be illustrated by the improved confinement of the debonding failure by the surrounding masonry (see Fig. 4). Within the ranges of parameters considered experimentally, τ_{max} for NSM FRP may be as much as double that for EB FRP, and δ_{max} almost an order of magnitude greater. For adhesively bonded joints outside the range of values and parameters considered experimentally, it is recommended that push-pull tests of the type shown in Fig. 2 be undertaken.

FRP REPAIRED WALLS SUBJECT TO OUT-OF-PLANE LOADING

As might be expected, experimental tests on URM walls have demonstrated that the application of FRP for strengthening does not affect the formation of crack patterns. Hence, the FRP is not activated until after the cracks have formed, similar to internal steel reinforcement in reinforced concrete. The behavior of walls subject to out-of-plane loading is described in this section. An overview of the behavior of URM walls under in-plane loading is given in the following section along with brief details of finite element modeling of FRP strengthened URM walls.

To illustrate the behavior of FRP repaired URM walls subject to out-of-plane loading Willis et al [1] repaired four walls that were previously tested under cyclic out-of-plane loading and were severely damaged. The walls were restrained along the top and bottom edges and had vertical returns such that the original walls acted in two-way bending. The walls also had window openings. As the vertical moment resistance of URM walls in two-way bending is typically not considered in the total capacity, the repair strategy adopted used vertically oriented FRP strips, as can be seen in Fig. 5a. Figure 5b illustrates the effectiveness of the technique by showing that the deformation capacity increased to such an extent that portions of the wall between FRP strips collapsed. Analysis of the FRP axial strain distribution showed that at collapse the FRP was approaching its IC debonding resistance.

(a) overall view of test set-up (b) failure by collapse of brick units

Figure 5. FRP repaired URM wall subject to out-of-plane loading

Figure 6 shows the static load-displacement behavior of the original unretrofitted wall (Control A), and the cyclic envelope response after loading demonstrating the significant loss of strength. Also superimposed in Fig. 6 are the static responses of three FRP repaired walls. It can be seen that the repair scheme was able to restore the original strength of the wall, and perhaps more significantly, improve the deformation capacity of the wall to such an extent that collapse of brick units occurred as in Fig. 5b.

The vertical strips were so effective that the capacity of the FRP repaired wall could be reasonably estimated from the vertical moment capacity using a standard strain based sectional analysis of a design strip of width equal to the FRP spacing [11]. The strain distribution would likely be governed by the IC debonding strain of the adhesively bonded FRP, which has an upper limit of the rupture strain. In addition, a rigid body analysis was developed to predict the out-of-plane displacement of an FRP repaired URM wall corresponding to the FRP strain [11]. For design purposes, it is recommended to limit the maximum out-of-plane displacement to the thickness of the brick units so that collapse is avoided.

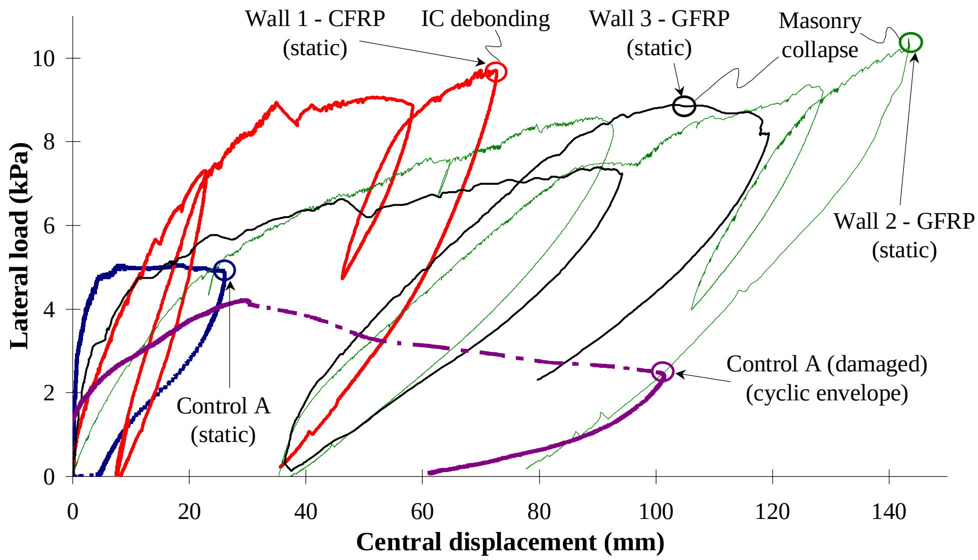


Figure 6. Out-of-plane load-displacement response of FRP strengthened URM walls

One of the walls tested was repaired with the NSM technique and failure was by premature FRP debonding as shown in Fig. 7, in a manner not yet quantified [12]. The NSM FRP strip debonded at a maximum strain significantly less than the IC debonding resistance due to the relative out-of-plane displacement of the rigid panels on either side of the diagonal crack. This caused the NSM FRP to pull out from the masonry in a direction perpendicular to that associated with IC debonding. This mechanism was not observed in the three EB cases tested. Such a failure is more likely to occur in the NSM technique because the FRP strip is bent about its strong axis and hence, the tendency for the FRP to pull out is greater. Although this premature debonding mechanism has yet to be quantified, it is postulated that it may be relatively easy to prevent by suitably anchoring the ends of the FRP. Specific details about forms of anchorage are beyond the scope of this paper.

Figure 7. Premature debonding failure of NSM Carbon FRP strip

FRP STRENGTHENED WALLS SUBJECT TO IN-PLANE SHEAR LOADING

Horizontally oriented FRP is typically used to strengthen URM walls subject to in-plane shear. However, recent diagonal tension tests on wallettes strengthened with vertically oriented NSM FRP strips, as shown in Fig. 8, have demonstrated the efficiency of this alternative [7]. Dilation of the mortar-brick interface must occur as sliding takes place along the (horizontal) bed joints. The dilation induces a tension force in the transverse (vertical) NSM FRP, which in turn develops a compressive stress normal to the bed joint to maintain equilibrium. This mechanism improves the frictional sliding resistance, effectively increasing the deformation capacity as demonstrated in the typical load-displacement response shown in Fig. 9.

(a) Unreinforced masonry (b) NSM FRP strengthened

Figure 8. Masonry wallette in diagonal tension test (at ultimate)

The load-displacement curves shown in Fig. 9 were determined from a two-dimensional plane stress finite element model. A masonry micro-model was adopted whereby the bricks and mortar interfaces are modeled discretely allowing the complex FRP debonding and interface sliding processes to be accurately simulated. The brick units were modeled with elastic quadratic elements and the mortar joints with non-linear zero-thickness interface elements such that failure will only occur along interfaces. Appropriate constitutive models were input for the interface elements [7] allowing for direct tension, interface shear/compression, compression, and normal uplift (dilation) as a function of normal compressive stress and inelastic shear displacement. Non-linear interface elements were also used to define the FRP-to-masonry interface based on an appropriate bond-slip model, similar to that shown in Fig. 3. The FRP was modeled using elastic truss elements with no dowel resistance where the FRP crosses mortar joints.

Since a two-dimensional FE model was used, asymmetric behavior or out-of-plane twisting of the wall that may take place due to the positioning of the FRP close to one face of the wall only is not accounted for. However despite this, Fig. 10a shows that even given the variability of masonry material properties, the proposed finite element model is able to capture the behavior of an FRP strengthened URM wallette, confirming the unique failure mechanism described previously. Further, as the maximum dilation is in the order of half a millimeter and for a typical bond-slip relationship for NSM FRP, it is highly unlikely that NSM FRP will debond. Figure 10b gives the finite element displaced shape which may be compared to that observed experimentally in Fig. 8b.

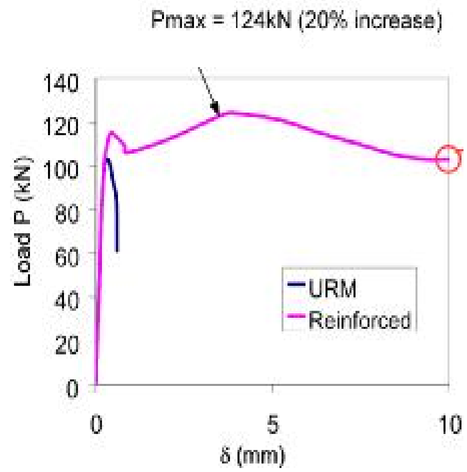
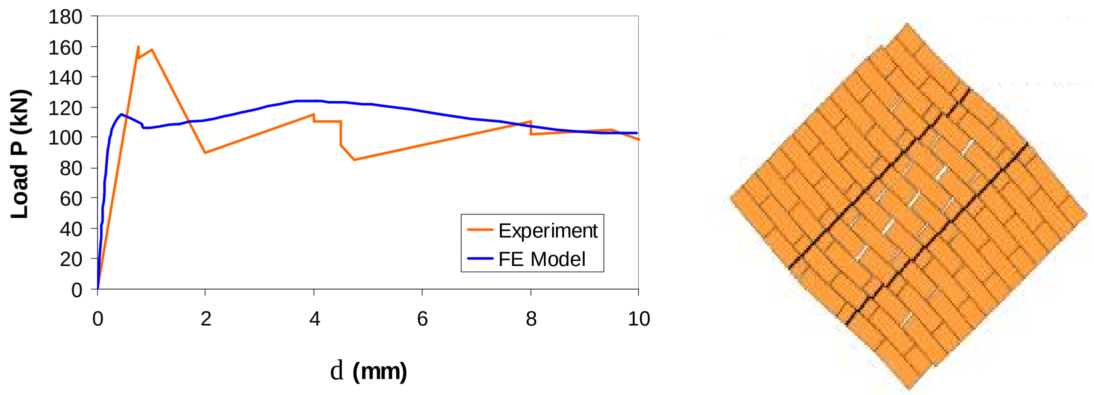


Figure 9. Comparison of typical load-displacement response



(a) Comparison of load-displacement response (b) Finite element displaced shape

Figure 10. Finite element prediction of FRP strengthened wallette

CONCLUSION

This paper presents a brief state-of-the-art review of FRP strengthening/repair of unreinforced masonry walls subject to out-of-plane or in-plane loading. It is demonstrated that adhesively bonded FRP systems are able to efficiently restore the strength of severely damaged walls, and more importantly, significantly enhance the deformation capacity, which is a major issue for unreinforced masonry walls subject to extreme wind or earthquake loading. It is also shown that the use of discrete NSM strips that maintain the aesthetic characteristics of masonry walls is an efficient alternative. The fundamental bi-linear bond-slip relationship is described, which is necessary in the analytical or numerical modeling of the FRP strengthened/repaired masonry walls. The efficiency of using only vertically oriented discrete FRP strips is illustrated to increase the vertical moment capacity and deformation capacity of walls subject to out-of-plane loading, as well as the strength and shear deformation capacity of walls subject to in-plane loading. Some details are also provided for the development of finite element models to simulate local deformation along mortar interfaces and debonding of the FRP.

REFERENCES

1. Willis, C.R., Yang, Q., Seracino, R. and Griffith, M.C. (2008) "Damaged masonry walls in two-way bending retrofitted with vertical FRP strips" *Construction and Building Materials*, in press.
2. Seracino, R., Yang, Q., Griffith, M.C. and Willis, C.R. (2006) "Push-pull tests on FRP retrofitted unreinforced masonry units." *Proceedings of the 19th Australasian Conference on Mechanics of Structures and Materials,* Christchurch, NZ, 29 Nov – 1 Dec.
3. Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L. (2002) "*FRP strengthened RC structures*" Wiley, London, 245 pp.
4. Oehlers, D.J. and Seracino, R. (2004) "*Design of FRP and steel plated RC structures: Retrofitting beams and slabs for strength, stiffness and ductility*" Elsevier, UK, 228 pp.
5. Petersen, R.B., Masia, M.J. and Seracino, R. (2007) "Influence of plate orientation and amount of precompression on the bond strength between NSM CFRP strips and masonry." *10th North America Masonry Conference,* St. Louis, USA, 3 – 6 June.
6. Yuan, H., Teng, J.G., Seracino, R., Wu, Z.S. and Yao, J. (2004) "Full-range behavior of FRP-to-concrete bonded joints." *Engineering Structures,* Vol. 26, pp 553-565.
7. Petersen, R.B., Masia, M.J. and Seracino, R. (2008) "Experimental verification of finite element model to predict the shear behavior of NSM FRP strengthened masonry walls." *Proceedings of the 14th International Brick and Block Masonry Conference,* Sydney, Australia, 17-20 Feb.
8. Seracino, R., Raizal Saifulnaz, M.R. and Oehlers, D.J. (2007) "Generic IC debonding resistances of EB and NSM plates." *Journal of Composites for Construction,* ASCE, Vol. 11, No. 1, pp 62-70.
9. Petersen, R.B., Masia, M.J. and Seracino, R. (2008) "Bond behavior of FRP-to-modern clay brick masonry joints: Influence of plate orientation and precompression." *Journal of Composites for Construction,* ASCE, submitted.
10. Willis, C.R., Yang, Q., Seracino, R. and Griffith, M.C. (2008) "Bond behavior of FRP retrofitted masonry." *Engineering Structures,* tentatively accepted.
11. Willis, C.R., Yang, Q., Griffith, M.C. and Seracino, R. (2007) "Analysis of Damaged URM Walls Retrofitted with Vertical FRP Strips Subjected to Out-of-plane Loading." *Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures,* Patras, Greece, 16-18 July.
12. Willis, C.R., Seracino, R., Wu, C. and Griffith, M.C. (2007) "Displacement induced and IC debonding in one-way beam tests." *1st Asia-Pacific Conference on FRP in Structures,* Hong Kong, China, 12-14 Dec.