



## **EXPERIMENTAL AND NUMERICAL INVESTIGATION INTO THE SHEAR BEHAVIOUR OF UNREINFORCED MASONRY PANELS RETROFITTED WITH FIBRE REINFORCED POLYMER STRIPS**

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### **ABSTRACT**

Inserting fibre reinforced polymer (FRP) strips into pre-cut grooves is an emerging technique for the retrofitting/strengthening of unreinforced masonry (URM) structures. This method, known as near surface mounting (NSM), provides significant advantages over externally bonded FRP strips in that it has less of an effect on the aesthetics of a structure and can sustain higher loading before debonding. As this technique is relatively new, few studies into the behaviour of masonry walls strengthened using this technique have been conducted. A combined experimental and numerical program was conducted to study the in-plane shear behaviour of masonry walls strengthened with NSM carbon FRP strips. Different reinforcement orientations were used, including: vertical; horizontal; and a combination of both. The FRP strips were designed to resist sliding along mortar bed joints and diagonal cracking. The first stage of the project involved characterising the bond between the FRP and the masonry using experimental pull tests (18 in total). The second stage of the project involved conducting diagonal tension/shear tests on masonry panels (4 URM and 7 strengthened). The third stage of the project involved developing a finite element model to help understand the experimental results. A general overview of the project, highlighting the main conclusions, is provided in this paper. In general, the FRP reinforcement was effective: it prevented the URM failure modes, and increased the ultimate load and ductility of the walls. Also, the finite element model reproduced the key behaviours observed during the experimental diagonal tension/shear tests.

**KEYWORDS:** bond, finite element, FRP, masonry, NSM, shear.

### **INTRODUCTION**

Damage caused by earthquakes has highlighted the potential vulnerability of unreinforced masonry (URM) buildings to earthquake loading. The technique of bonding fibre reinforced polymer (FRP) reinforcing materials to a URM wall is a relatively new retrofit alternative. The

FRP reinforcement is designed to provide tensile strength to a wall to increase its strength and ductility. Experimental researchers have tested several different FRP strengthening techniques for shear walls. These techniques include: bonding discrete FRP strips/sheets to the surface of a wall in a variety of different arrangements [1]; covering the whole surface of a wall with externally bonded FRP sheets [2]; structurally repointing FRP bars and strips [3]; and near-surface mounting (NSM) FRP bars and strips [4]. In the majority of tests the FRP reinforcement has been used to prevent diagonal cracking failure. Test results reported in the literature have demonstrated the effectiveness of using the proposed techniques.

The NSM method provides significant advantages over externally bonded FRP strips in that it has less of an effect on the aesthetics of a structure and can sustain higher loading before debonding. As this technique is relatively new, few studies into the behaviour of masonry walls strengthened using this technique have been conducted. Marshall and Sweeney (2002) [4] have used carbon FRP (CFRP) NSM strips to improve the in-plane flexural behaviour of masonry shear walls, but they did not use the strengthening technique to prevent sliding or diagonal cracking failure. Tinazzi and Nanni (2000) [3] strengthened URM shear panels using NSM circular glass FRP bars, but not strips. Thin rectangular strips are more efficient than circular bars, because the confinement around the strip is maximised.

The objective of this research was to study the in-plane shear behaviour of NSM FRP strengthened masonry walls. In particular, the objective was to determine the effectiveness of the technique and also the fundamental shear reinforcement mechanisms of NSM FRP reinforcement crossing a shear crack. The first specific aim was to experimentally characterise the shear bond-slip behaviour of the interface between the NSM FRP strip and masonry. The bond-slip behaviour represents the fundamental behaviour of the FRP-to-masonry interface. This relationship is required in numerical models to predict the behaviour of an FRP reinforced structure. The second specific aim was to study the in-plane shear behaviour of NSM FRP strengthened masonry walls using experiments and a rationally based, representative finite element model. The work conducted to achieve these aims is presented in this paper.

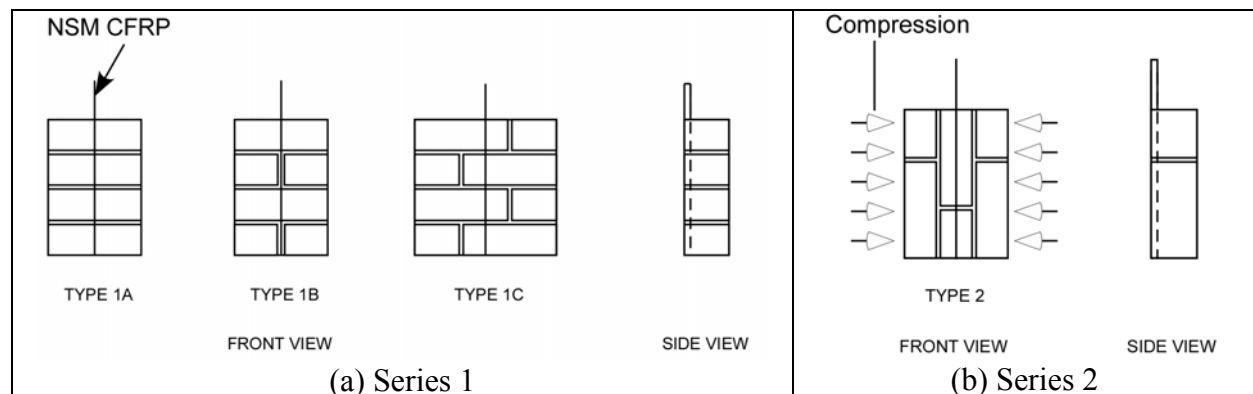
## **MATERIALS**

Walls and masonry assemblages were constructed using solid clay masonry units with nominal dimensions 230 mm long, 110 mm wide and 76 mm high. The flexural tensile strength of these units was 3.57 MPa, determined using lateral modulus of rupture tests [5]. The mortar used to construct the masonry walls and assemblages was mixed in batches with a mix ratio of 1:1:6 (cement:lime:sand by volume). The mortar joints were 10 mm thick. Carbon FRP (CFRP) strips 15 mm wide and 2.8 mm thick were used as the reinforcement. The strips had an elastic modulus of 210 000 N/mm<sup>2</sup> and rupture strain of 12 000  $\mu\epsilon$ . The FRP strips were constructed by gluing two FRP strips 1.4 mm thick together with an Araldite<sup>TM</sup> adhesive.

## **PULL TEST**

The experimental pull test was used to characterise the shear bond behaviour between the FRP and the masonry. The test involves subjecting FRP reinforcement, which is bonded to a masonry prism, to a direct tensile force. A detailed account of the pull test program is given in [6].

The test specimens are shown in Figure 1. In the first series of experiments the FRP was aligned in the vertical direction (perpendicular to the mortar bed joints). FRP was bonded to brick only (Type 1A and 1C) or alternating mortar joints and brick units (Type 1B). In the second series the FRP was aligned in the horizontal direction (parallel to the mortar bed joints). The FRP strips were glued, using epoxy, into rectangular grooves cut into the surface of the masonry walls/assemblages with a circular saw. The grooves were approximately 20 mm deep and 6 mm wide. The effect of compression perpendicular to the FRP strip was studied for Series 2 specimens. Compression forces may arise (after the installation of NSM FRP) due to: live loads; in-plane shear loads; and by confinement with vertical FRP reinforcement. Compression levels of 0 MPa, 0.5 MPa, and 1.0 MPa were adopted. To account for variability 3 specimens of each type were tested. The test setup is shown in Figure 2.



**Figure 1: Pull Test Specimens**

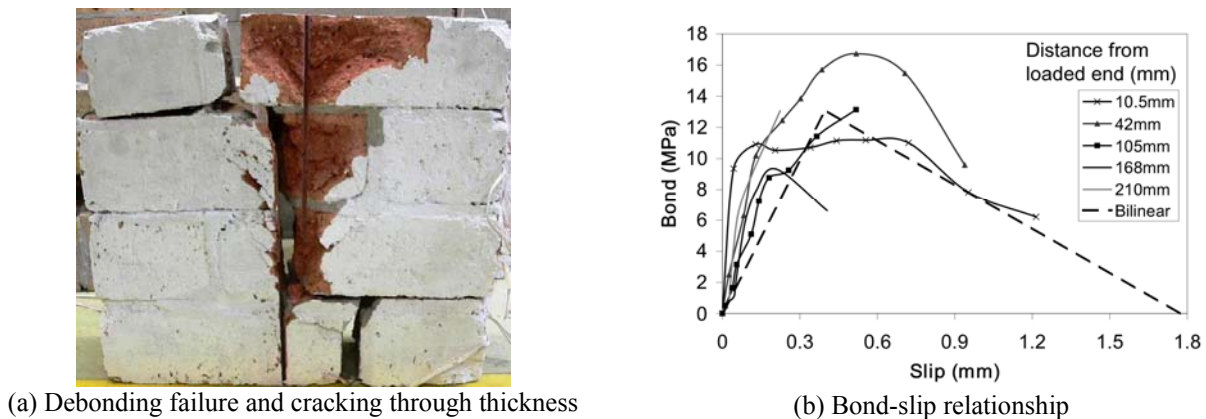


**Figure 2: Pull Test Setup**

Most specimens failed by debonding of the FRP from the masonry, through the brick (Figure 3a). After removing Series 1 specimens from the testing apparatus, cracking was observed in line with the FRP, extending through the thickness of the specimens. In two of the three Type C specimens a vertical crack formed completely through the specimen (Figure 3a). This kind of cracking in the direction of the reinforcement may have adverse effects in an FRP retrofitted wall. In fact, cracking through the thickness of the wall adversely affected one of the FRP strengthened wall panels (see section “Wall Panel Tests”).

The average bond strengths for each type of specimen are shown in Table 1. The maximum FRP strains are also included. The bond strength of the horizontally aligned FRP was lower than the bond strength of the vertically aligned FRP. However, compression applied perpendicular to the FRP strips increased the bond strength. The bond strength was reduced when the FRP strip passed through head (perpend) joints.

Strain gauges were attached to the FRP strips in order to calculate the local bond-slip relationship of the interface between the FRP and the masonry. Bond-slip relationships were determined for each test type. Strain gauges were used in one specimen for each test type. A total of 8 gauges were attached along the bonded length. Two gauges were used to measure strain in the unbonded length, 21 mm above the top surface of the specimen. The bond-slip relationships determined for the Type 1C specimen are shown in Figure 3b. Bilinear approximations were then fitted to the experimental data. These bilinear approximations were used to model the bond interface between the FRP and masonry in the FE model.



**Figure 3: Specimen Type 1C Results**

**Table 1: Average Bond Strength of Pull Test Specimens**

Specimen Type	1A	1B	1C	2 (P=0)	2(P=0.5 MPa)	2 (P=1 MPa)
Avg. Bond Strength (kN)	78.7	64.9	72.6	54.1	63.5	75.1
Max. FRP strain ( $\mu\epsilon$ )	8835	7420	8090	6089	7398	8503

### WALL PANEL TESTS

Four URM walls and seven strengthened walls were tested in diagonal tension/shear (ASTM E519-93 [7]). All of the wall specimens were 1.2 m x 1.2 m square. The flexural tensile bond strength of each mortar batch used in the construction of the walls is given in Table 2. The bond strengths were determined using the AS3700 bond wrench test [8]. During the construction of walls V4B, V2H2B and H4B, and also at the start of construction of walls URM-3 and URM-4 the mortar was re-tempered (water added) to improve its workability. The bond strength of the retempered mortar was also determined. These batches are identified as ‘batch no.+W’ in Table 2. The height of the wall during construction when the water was added was not recorded. Wall URM-4 was constructed over 2 days, with a new mortar batch used on the second day of construction. The height of this wall, where the new mortar batch was started, was not recorded.

**Table 2: Wall Panel Bond Strength Data**

Specimen	Mortar batch (first batch)	Bond Strength (N/mm <sup>2</sup> )	Mortar batch (second batch)	Bond Strength (N/mm <sup>2</sup> )
URM-1	5	1.26 (COV 32%)	-	-
URM-2	5	1.26 (COV 32%)	-	-
URM-3	5+W	0.41 (COV 59%)	-	-
URM-4	3+W	0.31 (COV 57%) <sup>a</sup>	4	0.57 (COV 48%)
V2	4	0.57 (COV 48%)	-	-
V4A	2	0.49 (COV 37%)	-	-
V4B	2	0.49 (COV 37%)	2+W	0.29 (COV 46%)
V2H2A	3	0.47 (COV 47%)	-	-
V2H2B	3	0.47 (COV 47%)	3+W	0.31 (COV 57%) <sup>a</sup>
H4A	1	1.25 (COV 51%)	-	-
H4B	1	1.25 (COV 51%)	1+W	0.65 (COV 34%)

<sup>a</sup> Only 5 joints tested. Pier constructed with other 5 joints broke during transport.

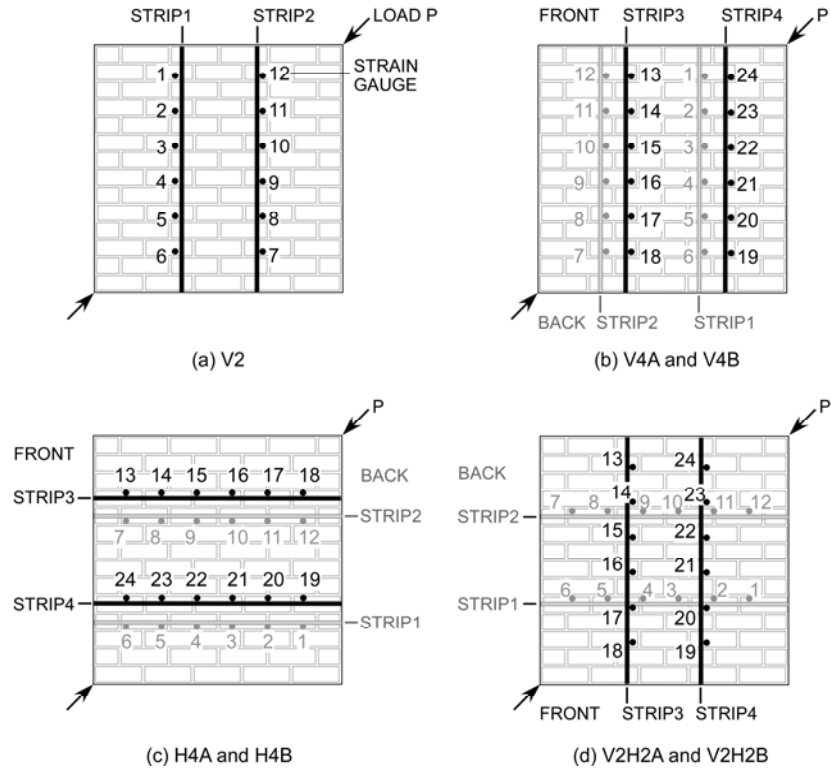
The reinforcement schemes used for the strengthened walls are shown in Figure 4. Wall V2 was reinforced with 2 vertical strips on one side of the wall (Figure 4a). Walls V4A and V4B were reinforced with 2 vertical strips on each side of the wall (Figure 4b). Walls H4A and H4B were reinforced with 2 horizontal strips on each side of the wall (Figure 4c). The strips in walls V4A, V4B, H4A and H4B were staggered to prevent through brick cracking between strips on opposite sides of the wall. Walls V2H2A and V2H2B were reinforced with 2 vertical strips on one side of the wall and 2 horizontal strips on the other side of the wall (Figure 4d). In all walls the vertical reinforcement was located midway between mortar head joints and the horizontal reinforcement was located mid-height between the mortar bed joints.

Potentiometers were used to measure the vertical displacement (along the loaded diagonal), on each side of the wall, in accordance with ASTM E519-93 [7]. The gauge length was 1300 mm.

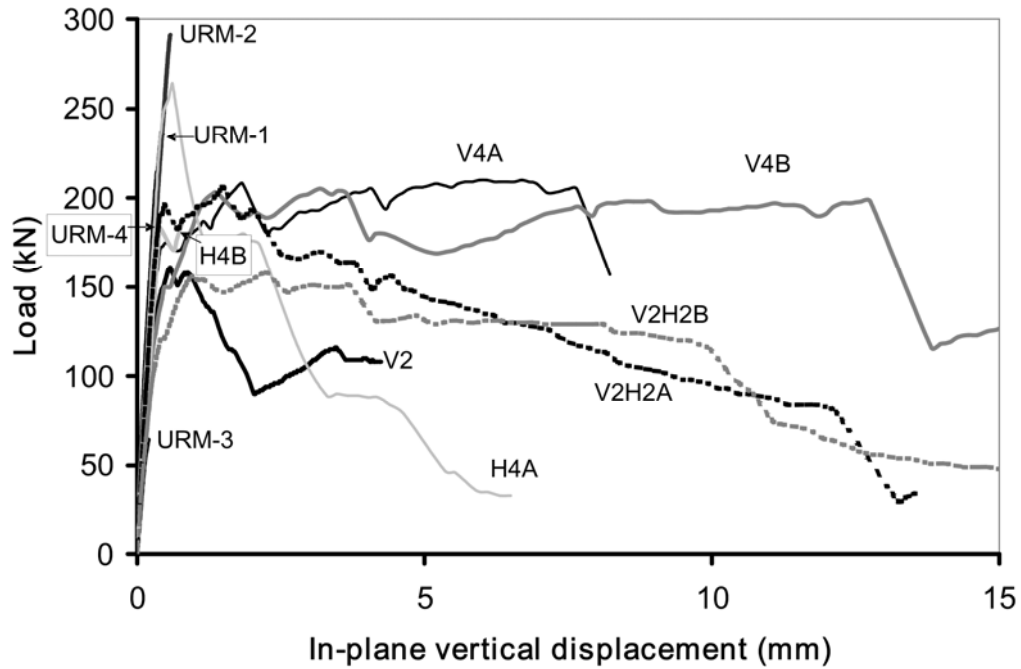
The load versus vertical displacement behaviours of all walls are shown in Figure 5. The displacement was the average of the potentiometer gauge displacements on each side of the wall. The URM walls behaved approximately linearly until brittle failure occurred. The URM walls with weak bond strength (URM-3 and URM-4) failed by sliding along the bed joints (Figure 6a). The URM walls with strong mortar (URM-1 and URM-2) failed by diagonal cracking through brick units and mortar joints. The strength variation of the URM specimens was a result of the variation in bond strength between walls (see Table 2).

In the walls reinforced with vertical strips (V2, V4A & V4B, V2H2A & V2H2B) the URM failure mode was prevented and the ultimate load and ductility of these walls was increased. The presence of the reinforcement also allowed more cracks to develop throughout the wall (Figures 6b, 6c and 6f). The tensile strains in the FRP strips increased (in the vicinity of cracks) as the vertical displacement increased. It was highly likely that the vertical reinforcement prevented URM sliding failure by restraining the opening (dilation) of the sliding cracks that developed through the mortar bed joints. The restraint of dilation would result in an increased resistance to frictional sliding. It was also possible that the vertical reinforcement provided some dowel action. In many tests, however, large bending of the strips was observed across sliding cracks,

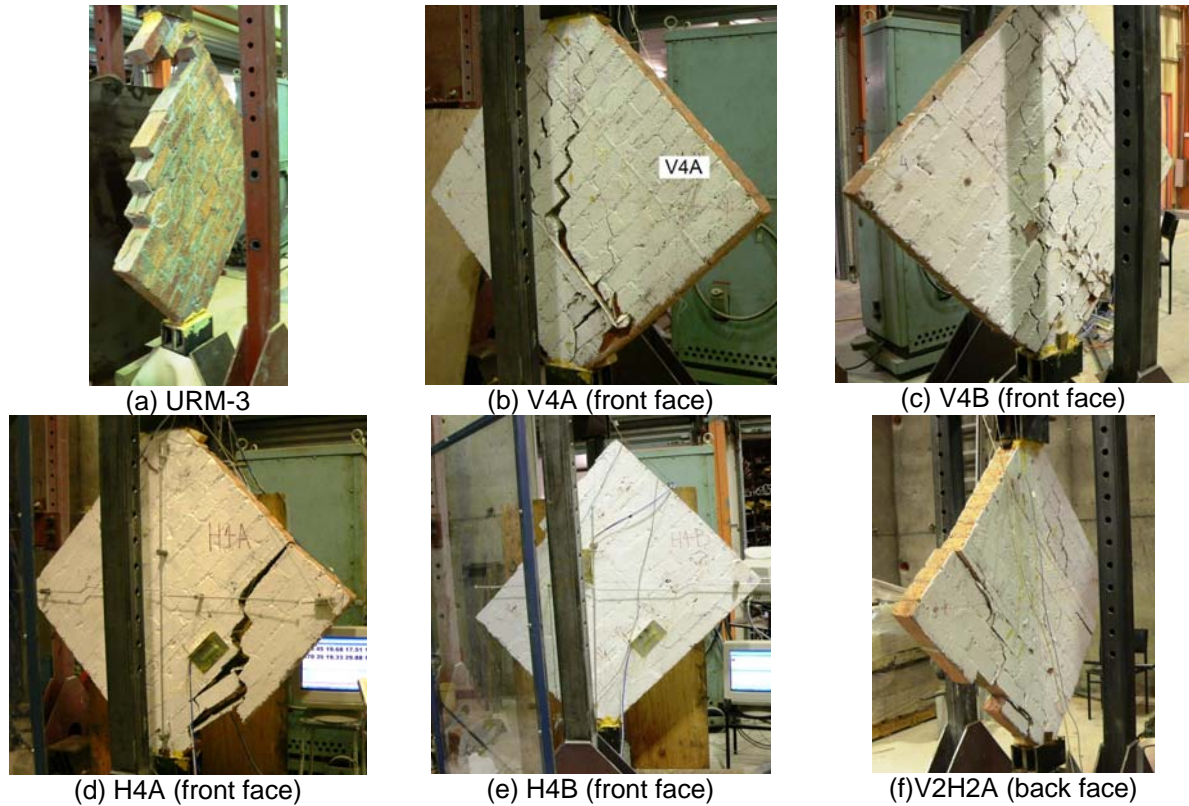
suggesting that dowel strength was negligible. In walls V2H2A and V2H2B the horizontal reinforcement restrained the opening of diagonal cracks.



**Figure 4: Wall Panel Reinforcement Schemes**



**Figure 5: Load-Displacement Behaviour of all Specimens**



**Figure 6: Failure Modes of Wall Panel Tests**

The non-symmetrical reinforcement schemes (in V2, V2H2A and V2H2B) caused out-of-plane bending, which reduced the load carrying capacity of the walls. The out-of-plane displacement in wall V2H2A is shown in Figure 6f. It is possible that in a real wall with additional edge restraint the out-of-plane displacement would not be as significant.

Walls V4A and V4B failed when the bottom of FRP strip 3 debonded from the wall. Debonding of the vertical reinforcement in walls V2H2A and V2H2B also occurred at the end of the test. In wall V4A cracking along the inside edge of strip 3 (between strips 3 and 4) was observed (Figure 6b). This cracking developed through the thickness of the wall and resulted in failure sooner (lower displacement) than V4B (where this type of cracking was not observed). It is likely that the groove cut into the masonry for the NSM FRP influenced this type of cracking.

Walls reinforced with only horizontal strips performed the worst. The reinforcement in H4A did not contribute to the load capacity of the wall. The reinforcement (strip 1) only prevented a section of masonry from falling off the wall (Figure 6d). In wall H4B failure occurred along an unstrengthened joint, after a very small increase in strength and ductility (Figure 6e).

The maximum measured FRP strain in each wall is presented in Table 3. The strain gauges were positioned close to the mortar joints where most cracks developed. Therefore it is likely that in most cases the measured strains are close to (or equal to) the maximum strains along the strip. The maximum strains measured in the debonding strips are also included in Table 3 (if different). In general the debonding strains were lower than those recorded in the pull tests ( $8090 \mu\epsilon$  -

specimen type 1C). It is likely that some cracking along the inside edge of the FRP strip (most dramatic in wall V4A – see Figure 6b) caused the reduction in bond strength.

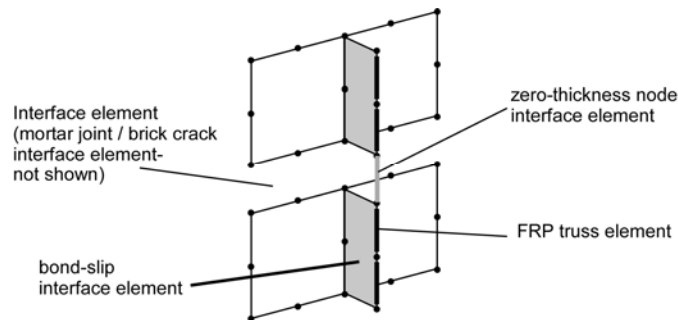
**Table 3: Maximum and Debonding FRP Strain in Wall Panel Tests**

Wall	V2	V4A	V4B	H4A	H4B	V2H2A	V2H2B
Max Strain ( $\mu\epsilon$ ) (strip/gauge)	3100 (1/3)	4500 (1/3)	6242 (3/16)	8900 (1/2)	1600 (3/17)	5200 (4/16)	9850 (3/18)
Debond Strain ( $\mu\epsilon$ ) (strip/gauge)	N/A	4000 (3/17)	as above	N/A	N/A	3800 (3/16)	as above

### FINITE ELEMENT MODEL

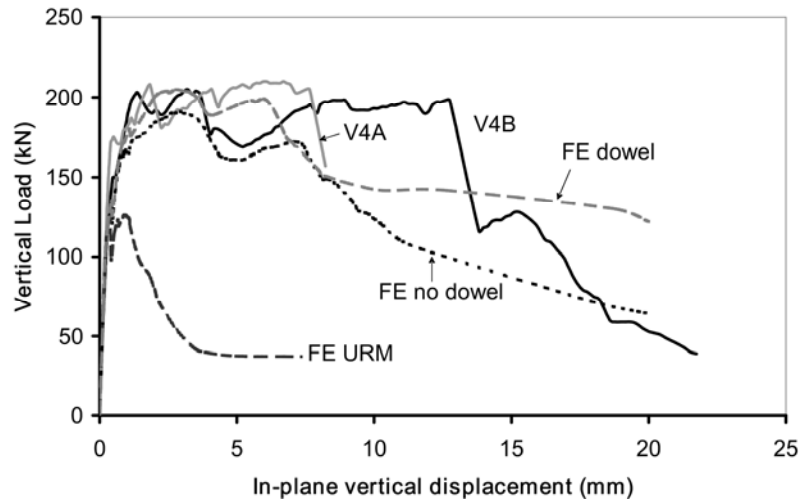
All of the wall panel tests were simulated using the displacement finite element (FE) method. The commercial FE analysis package DIANA was used for the analysis. To model the masonry the simplified micro-modelling approach was adopted. Expanded brick units were represented by plane stress continuum elements and the behaviour of the mortar joints and the unit/mortar interface was lumped into zero-thickness interface elements. Interface elements were also used to model potential brick cracking at the mid-length of the brick. The crack-shear-crush material model included in DIANA was used to model the behaviour of the mortar joint interface elements. As the name implies, this material model includes cracking under tension and shear, shear-friction, and crushing under compression and shear. For the potential brick crack interface element a linear tension softening model was used. The material properties required for the masonry model were determined from experimental characterisation tests. These tests included: a) compression tests on masonry piers; b) Torsion shear tests [9]; c) Brick lateral modulus of rupture tests [5]; and d) bond wrench tests [8].

FRP strips were modelled using truss elements (Figure 7). The FRP elements were attached to the masonry model using interface elements. The behaviour of the interface element in the shear direction (longitudinal direction of the reinforcement) was modelled using the bond-slip models determined from the experimental pull tests (e.g. Figure 3b). The FRP was connected across mortar-joint/potential-crack interface elements using a node interface element. In the longitudinal direction a high stiffness was given to the node interface element to make the FRP continuous across the joint. In the transverse direction (i.e. the direction of mortar joint or brick crack sliding) a dowel relationship was used. Two dowel relationships were adopted: zero dowel strength and a 7 kN dowel strength. This dowel strength was estimated using an FE model (not described here). Dowel action was modelled to investigate whether it would be significant.

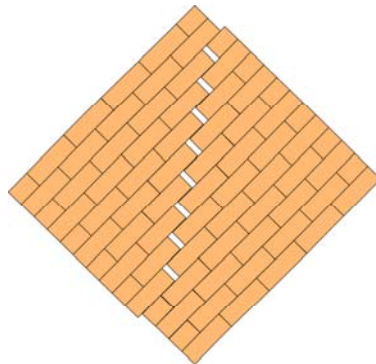


**Figure 7: FRP attachment in FE model**

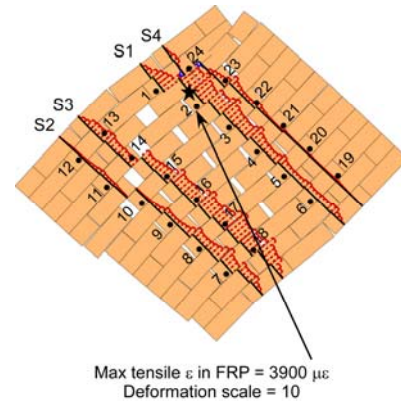




(a) Load displacement behaviour of V4 FE model and URM model



(b) Typical failure mode of URM model



(c) Failure mode of V4 FE model with no dowel strength (13 mm wall vertical displacement)

**Figure 8: Example of FE analysis results (V4 model and URM model)**

The FE model reproduced the key behaviours observed in the experiments for both the unreinforced and FRP strengthened walls. The load-displacement, crack development and the FRP reinforcement contribution was similar until out-of-plane effects became significant in some of the experiments (due to non-symmetric reinforcement). FRP debonding did not occur in the FE models, instead the walls failed by either sliding, or crushing at the top of the wall. Example results of the FE analysis are shown in Figure 8 for a model reinforced with 4 vertical strips. The failure mode of the URM FE model is also included in Figure 8b. By simulating the strengthened wall models with, and without, dowel strength it was concluded that dowel action was a negligible, or possibly a secondary, shear resisting mechanism. The primary shear resisting mechanism is then the increase in friction from the FRP resisting dilation.

## CONCLUSIONS AND FUTURE WORK

The research has contributed to gaining a fundamental understanding of: the shear bond behaviour between NSM FRP and masonry; and the shear reinforcement mechanism of NSM FRP bonded to unreinforced masonry. From the pull tests it was found that the orientation of the FRP strip affected the bond behaviour, and compression applied perpendicular to the strip

increased the bond strength. From the wall tests it was found that vertical FRP strips were the most effective. Horizontal strips could not prevent sliding failure. The vertical reinforcement acted in tension to restrain shear induced dilation and prevent sliding. The dowel strength of the vertical reinforcement did not likely contribute significantly to the shear resistance of the masonry. This was confirmed with the finite element model. Future work will be aimed at investigating the behaviour of walls subjected to cyclic in-plane lateral loading. Rationally based design equations/procedures also need to be developed.

### **ACKNOWLEDGEMENTS**

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