# Application of Brittle Materials to Strengthen Masonry

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# Application of Brittle Materials to Strengthen Masonry

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**ABSTRACT**

*Fibre Reinforced Polymer Strengthening (FRP) has become a popular method for retrofitting masonry structures. It is easily applied by attaching bonding either dry fibre mats or pre-formed plates to an existing structure. The ease of installation, the lightweight materials used, and their low corrosion rates have resulted in FRP strengthening becoming the strengthening method of choice for many applications. Both the FRP composite strengthening and the adhesive joint, however, are brittle. Brittle failure is accompanied by imperfection sensitivity, a lack of energy dissipation during cyclic loading, and an inability to redistribute load paths when unpredicted loads are applied to a structure. Furthermore, the stress in the FRP strengthening is prevented from approaching its ultimate capacity, by the adhesive connection failure.*

*If the growth of the debonded region of strengthening is halted by a positive anchor, the FRP will act as a simple elastic element with a length defined by the spacing of the anchorages. As an in-plane shear crack opens in the masonry, load will be transferred to the FRP, and furthermore, the FRP confines the masonry, increasing the shear load that it carries and the ductility of the system. This paper reports preliminary tests in which unbonded FRP 'bandages' were applied to small masonry panels, demonstrating the technique as an alternative to bonded strengthening.*

**KEYWORDS**

Fibre reinforced polymer, Strengthening, Adhesive, Ductility

## 1 INTRODUCTION

Structural refurbishment is ever more important to maintain our existing stock of ageing buildings whilst meeting society's changing demands. This is especially true given the heightened awareness of engineering sustainability; refurbishment helps avoid the unnecessary expense, disruption and environmental impact of demolition and rebuilding.

Structural refurbishment works are often referred to as 'strengthening', an accurate description if the aim is to increase the load capacity of a structure, or to reinstate load capacity that has been lost due to corrosion or other degradation. In other cases, the aim of the refurbishment work is not to increase the structure's strength, but might be to increase its stiffness, improve structural integrity, improve dynamic performance, make good construction errors, account for foundation movement, or alter the structural form to accommodate a change in use [De Lorenzis *et al.* 2008].

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### 1.1 Bonded Fibre-Reinforced Polymer Reinforcement

Fibre-reinforced polymer (FRP) strengthening has joined the plethora of refurbishment solutions relatively recently. In some applications (particularly for flexural strengthening of concrete) it has virtually become the default strengthening method, and it is certainly a useful technique for refurbishing masonry construction [De Lorenzis *et al.* 2008; Triantafillou, 1998].
Bonded FRP strengthening is convenient and quick to apply in comparison to traditional refurbishment techniques such as steel or concrete solutions. Surface preparation is necessary to expose a sound masonry substrate, to which the FRP strengthening is bonded using ambient-cure adhesives. The FRP might be applied as a dry fabric that is impregnated with adhesive on the wall (commonly referred to as 'wallpapering'). Alternatively, pre-formed FRP strips can be made off-site and bonded to the wall [Schwegler 1995].

The popularity of bonded FRP strengthening is largely due to the ease with it can be applied without major disruption to the structure. The materials are lightweight, which helps access and avoids additional permanent loads that might be detrimental to the structure's dynamic performance during an earthquake [Triantafillou 1998]. There is certainly a growing body of laboratory based research demonstrating the benefits of bonded FRP strengthening, but it should not be seen as a universal solution to masonry refurbishment. Amongst the issues that must be considered are:

- The scope of research to date is relatively limited. Small-scale laboratory research on idealised specimens must not be confused for real applications. Neither should prior application be used as proof that the system works: few of the ever-growing population of structures refurbished with bonded FRP have been subjected to the extreme events for which the FRP was required.
- Bonded FRP strengthening has poor fire performance, as ambient-cure epoxy adhesive are usually used. These epoxies can have glass-transition temperatures as low as 60°C, are flammable, and give off toxic fumes during a fire [Bisby *et al.* 2005].
- The long-term reliability of the systems is largely unproven.
- FRPs are impermeable to moisture transport.

### 1.2 Bonded FRP Strengthening for In-Plane Shear

One application of bonded FRP is to increase the in-plane strength of masonry panels [e.g.: Marshall *et al*. 1999; Schwegler 1995; Stratford *et al.* 2004]. Figure1 shows a typical bonded strengthening application using sheet FRP (Fig.1, left). The load capacity of the masonry panel can be significantly increased using bonded FRP strengthening. The FRP bridges the diagonal crack that forms within the masonry (Fig.1, right); the load capacity of the masonry is increased (i) due to the tensile tie that forms in the FRP and (ii) the additional friction that can be carried across the cracked masonry joint due to confinement of the masonry by the FRP. Compatibility must be satisfied between the FRP and the masonry; hence a band of FRP unbonds from masonry and propagates away from the diagonal crack as it opens. This bond failure occurs within the weakest link of the adhesive joint, which is just below the surface of the masonry bricks [Stratford *et al.* 2004].

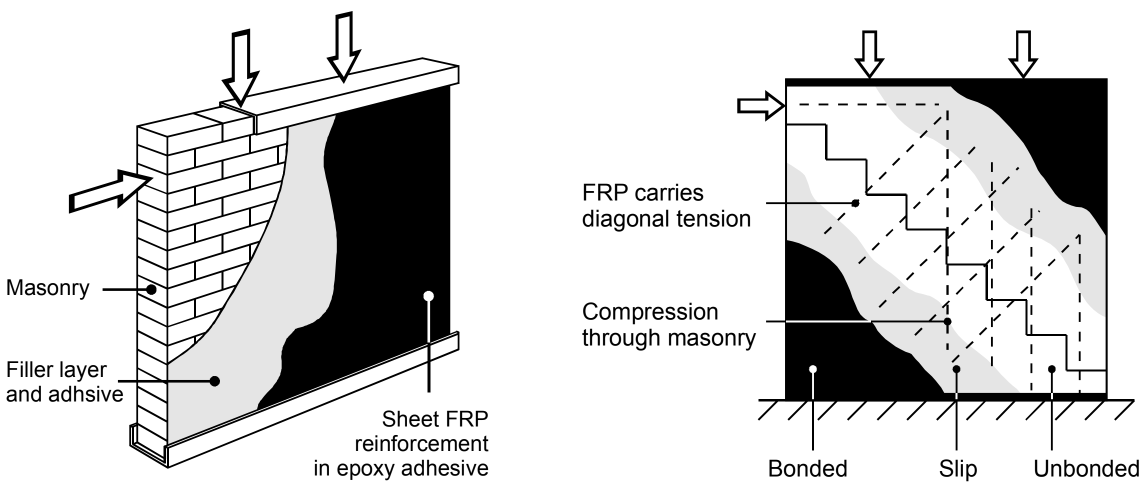


**Figure 1.** Bonded FRP in-plane shear strengthening. Failure of the strengthened masonry system (right) is characterised by diagonal cracking of the masonry panel, accompanied by unbonding of a band of the FRP strengthening [Stratford *et. al* 2004].

The increase in strength due to the bonded FRP can be useful, but it is also important to examine the ductility of the strengthened system, which has important implications for design. Perhaps the most obvious requirement for ductility is during an earthquake, when sustained energy dissipation is necessary under cyclic loading; however, ductility is also a fundamental requirement of structural design, as it underpins the lower-bound (or safe load) theory of plasticity, which allows design to proceed without understanding the exact equilibrium state provided stress redistribution can occur [Calladine 1969]. It is particularly important to recognize that both the FRP and the FRP-masonry bond failure are brittle and that the strengthened panel only displays ductility by virtue of frictional sliding between the two faces of the cracked masonry.

Furthermore, the brittle bond failure is sensitive to imperfections, which might be due to poor workmanship (such as poor surface preparation, inadequate wetting of the FRP or the FRP not being flat), or defects within the bricks. An additional consequence of the brittle bond failure is that the bond cannot dissipate energy once broken, which is of particular concern during multiple reverse loading cycles during an earthquake. Whilst research [e.g.: Marshall *et al*. 1999] has demonstrated that bonded FRP strengthening can be used for laboratory applied cyclic loading, the stress state in a real structure during a real earthquake could be very different. It is difficult to see how bonded FRP strengthening for real structures can be safely designed if it relies on brittle bond between the FRP and masonry.

Brittle unbonding, however, can be halted be introducing additional anchorage between the FRP and the masonry. For example, Khalifa *et al.* [1999] introduce a positive anchorage by chasing out a horizontal joint in the masonry and trapping the FRP sheet into this joint behind a bonded FRP bar. Alternatively, bundles of fibres can be bonded into holes drilled in the masonry, then splayed out and banded to the FRP sheet [Burr 2004]. Hall *et al.* (2002) demonstrated the use of a steel anchorage to trap the end of the FRP at the ground and to provide ductility to under-reinforced masonry buildings.

### 1.3 Unbonded FRP Strengthening

If the adhesive bond needs to be supplemented with additional anchorages between the FRP and masonry, it is natural to question whether the FRP need be bonded to the masonry at all. Eliminating the adhesive bond and using well defined anchorages has a number of desirable consequences:

- Extensive surface preparation is not required. The debris and dust from surface preparation requires careful handling for health and safety, and environmental considerations.
- Less reliance on a high quality of workmanship, and upon the unknown defects within the masonry.
- Greatly reduced use of adhesives, with less emission of volatile organics and improved fire performance.
- Improved reversibility, particularly desirable in heritage structures: the strengthening only disrupts the existing structure at the anchorage points, and can be more easily removed.
- The anchorage positions can be adjusted to ensure that the FRP deformation is compatible with the masonry.

Triantafillou and Fardis [1997] investigated placing unbonded FRP tendons around a structure, anchored only at their ends. These are post-tensioned to provide horizontal confinement of the structure and improve its structural integrity.

This paper investigates the application of unbonded FRP 'bandages' to the in-plane performance of masonry panels. It describes tests upon 'wallettes' loaded in shear-compression to induce a shear crack. The scope of the tests is limited, this being only a preliminary study, but the potential of unbonded FRP strengthening is demonstrated.

## 2 TEST METHODOLOGY

The aim of these preliminary tests was to investigate the composite action of a masonry panel and an unbonded FRP 'bandage'. Tests were undertaken on small-scale 'wallette' specimens, as shown in Fig. 2. The masonry panel fails be propagation of a diagonal crack across the specimen. As the crack opens, the bandage will stretch and pick up load, until it reaches its ultimate, brittle, strain capacity. It should be noted that the FRP bandages applied to these specimens are shorter than would be expected in a real application.

The wallette was loaded in compression ($W$) across one of its diagonals using a 1000kN load-controlled universal test machine, using steel spreader pieces to avoid crushing of the corners. The FRP 'bandage' strengthening was wrapped across the other diagonal. At the left side of the wall in Fig. 2, the FRP wrapped around a steel spreader, radiused to minimise stress concentrations in the FRP. The FRP was clamped and bonded to a steel plate at the right side of the wall. The FRP could be tensioned against the wall by tightening four bolts (*F* in the figure).

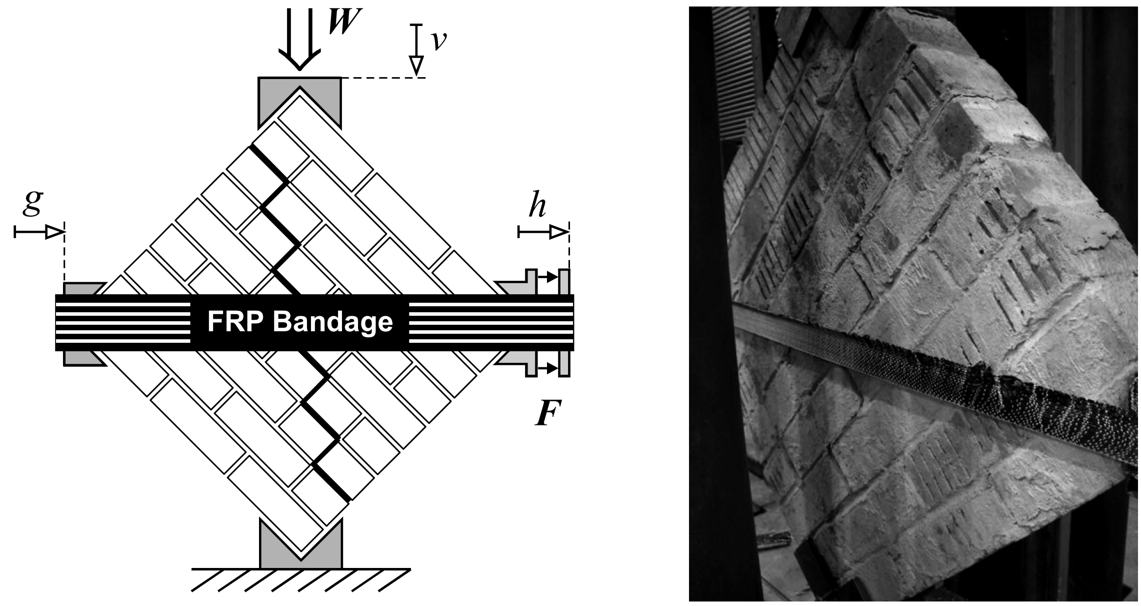


**Figure 2.** Schematic arrangement of strengthened wallette, not to scale (left), with strengthened wallette in test machine (right).

During the test, the following were recorded:

- the applied vertical load ($W$) and vertical displacement ($v$);
- the stretch of the bandage ($h$-$g$) by means of the horizontal displacement at each end of the bandage; and
- the force in the bandage ($F$) by means of four strain gauges bonded into the steel spreader and clamp at the right of the specimen and calibrated to give force.

Seven wallettes were constructed from clay bricks (215 × 100 × 65mm, Young's modulus = 9GPa) and cement mortar. Each wallette was 3 bricks wide and 9 bricks deep, with 10mm mortar joints, to give a panel 665 × 665mm.

The FRP bandage used a high strength CFRP tape with unidirectional fibres, 50mm wide and with a 0.2mm nominal thickness. The CFRP was impregnated with an ambient-cure epoxy resin, to allow stress transfer between the fibres. Tests on the bandage showed that one layer of bandage had an axial stiffness of 3.19kN/mm, for the same length of bandage as used on the wallettes.

Table 1 lists the details of each test specimen, including the mean cube strength of the mortar (based on 3 cubes from each mix). The first test was tested without an FRP bandage; the remainder either had a single wrap (2 layers), or two wraps (4 layers) of FRP. It proved difficult to set the tension in the bandage to a particular initial value, so more emphasise was placed on ensuring that the tension was the same on both sides of the wallette. A nominal low initial tension was applied in tests 2, 3 and 4, a moderate initial tension to test 6, and a high initial tension in tests 7 and 8. Test 6 was unintentionally pre-cracked prior to testing along the third mortar joint from the top of the specimen, but allowed pre-cracked behaviour to be studied.

An additional mix of mortar was used to make construct 20 'triplet' specimens, which were tested to determine the shear strength of the mortar joint between the clay bricks used (similar to the test method given in BS EN 1055-3:2002). The triplet tests were used to give the following peak shear strength ($\tau_{peak}$) and post-peak residual shear strength ($\tau_{residual}$) variation with confining stress ($\sigma$):

$$\tau_{peak} = \tan 38° \times \sigma + 1.90 \text{ N/mm}^2, \qquad \tau_{residual} = \tan 30° \times \sigma + 1.59 \text{ N/mm}^2 \qquad (1)$$

**Table 1.** Details of the test specimens.

| *Test number* | *Number of layers of CFRP in bandage* | *Initial Tension, T* [kN] | *Mean mortar cube strength, $f_{cu}$* [N/mm$^2$] |
|---|---|---|---|
| 1 | 0 | - | 8.3 |
| 2 | 2 | 1.5 | 5.4 |
| 3 | 2 | 0.6 | 6.1 |
| 4 | 4 | 1.8 | 5.5 |
| 5 | 4 | 3.0 | 6.4 |
| 6 (pre-cracked) | 2 | 10 | 6.1 |
| 7 | 4 | 7.4 | 4.3 |
| Triplet tests | - | - | 6.0 |

## 3 EXPERIMENTAL RESULTS AND INTERPRETATION

The masonry wallettes all failed in broadly the same manor: a crack formed perpendicular to the tensile diagonal of the specimen (as indicated in Fig. 2) and the FRP bandage picked up load as the crack opened until the ultimate capacity of the FRP was reached. Failure of the FRP was at the clamped joint, due to the stress concentrations at that position. Table 2 gives further details of the load at which the first crack opening was observed, the peak recorded load, and the ultimate displacement for each test; Figure 3 shows the load-displacement results.

**Table 2.** Headline results and failure modes for the tested wallettes.

| Test number | Load at first cracking (kN) | Peak load (kN) | Displacement at failure (mm) | Failure mode |
|---|---|---|---|---|
| 1 | 88 | | 8 | Brittle diagonal crack |
| 2 | 89 | 104 | 31 | Large crack opening, ultimate failure of bandage at clamp. |
| 3 | 95 | 133 | 25 | Large crack opening, ultimate failure of bandage at clamp. |
| 4 | 87 | 106 | 20 | Large crack opening, ultimate failure of bandage at clamp. |
| 5 | 96 | 100 | 13 | Crack opening followed by ultimate failure of bandage at clamp. |
| 6 | 0 (precracked) | 103 | 12 | Crack followed pre-cracked joint followed by ultimate failure of bandage at clamp. |
| 7 | 101 | 122 | 15 | Crack opening, followed by ultimate failure of bandage at clamp. |

The FRP had only a small effect on the load at which first cracking occurred compared to the plain masonry specimen (test 1). The first cracking load was increased slightly by applying additional initial tension, as is to be expected.

After first cracking, there was a drop in load as the joint adhesion was broken and the masonry joint transferred to a frictional mode of stress transfer. The exception to this was test 3, in which the masonry joint carried higher than expected loads after first cracking. As the vertical displacement and hence crack opening increased, the FRP stretched and carried significant load. There was a modest increase in load capacity of the specimens, but more significant was the increase in deflection capacity due to the confinement provided by the FRP bandage. This was limited by the deflection capacity of the FRP and consequently the specimens with low initial tension performed exhibited the greatest deflection capacity. It should be noted, however, that the FRP failed due to the stress concentration where the FRP was bonded and bolted between two steel plates, and was not carefully controlled, possibly resulting in variations between the tests.

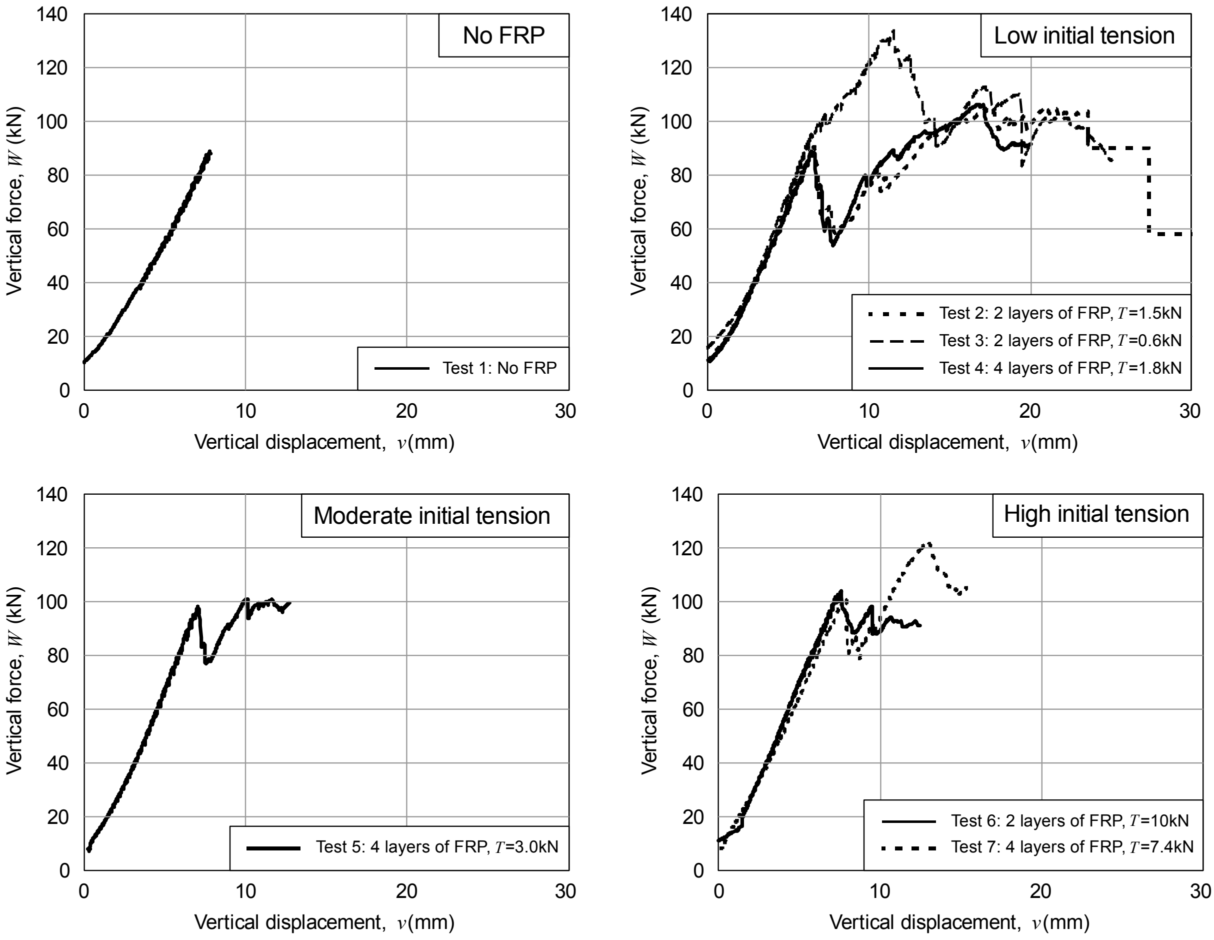


**Figure 3.** Load - vertical deflection results for all wallette tests.

Figures 4, 5, and 6 focus on the results from Test 3 (low initial tension, 2 layers of FRP); Test 4 (low initial tension, 4 layers of FRP) and Test 7 (high initial tension, 4 layers of FRP). Figure 4 records the difference in horizontal deflection across the specimen, (*h-g*) in Fig. 2, which is a measure of the stretch of the bandage. The results show that the bandage has negligible contribution prior to first cracking, with an approximately linear stretching of the bandage following cracking that indicates simple shearing along the cracked surface. Test 4 had 4 layers of FRP and during the test it was observed that there was some initial slack in the inner layer of FRP compared to the outer layer, which could explain the bi-linear response.

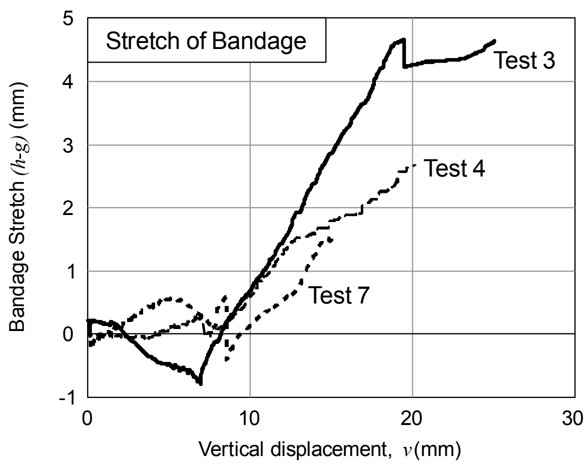


**Figure 4.** Stretch of bandage, based upon horizontal deflection measurements.

Figure 5 records the force in the FRP recorded using the strain gauges on the steel clamp (*F* in Fig. 2), and also shows that the bandage load was maintained at the initial tension until after first cracking. The plateauing of bandage force at high loads requires further investigation, but is believed to be due to a combination of slip in the FRP clamp, and progressive failure of the fibres in the FRP.

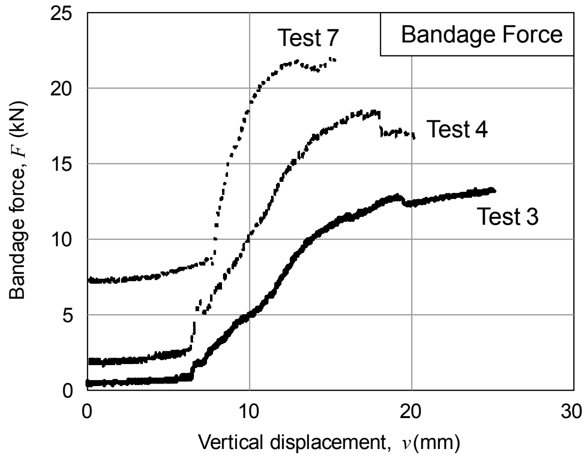


**Figure 5.** Force in bandage from strain gauge measurements.

Figure 6 gives the ratio between the shear (*S*) and normal (*N*) forces acting across the diagonal cracked joint, and shows that once frictional sliding had developed across the crack, it carries load according to the angles of friction obtained from the triplet test results (Eqn. 1). Force resolution gives the shear and normal forces as:

$$S = (W - F)/\sqrt{2}\,, \qquad N = (W + F)/\sqrt{2} \tag{2}$$

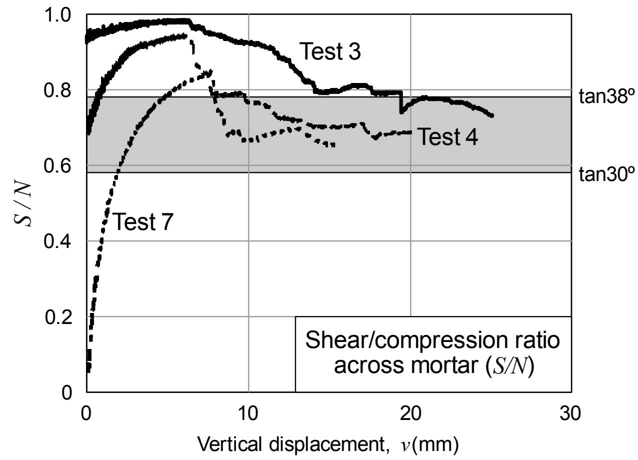


**Figure 6.** The ratio of shear to normal compression force through the masonry. The grey band indicates the range of friction angle deduced from the triplet tests (Eqn. 1).

## 4 DISCUSSION

This small series of tests has demonstrated the potential application of unbonded FRP to increase the in-plane deformation capacity and strength of masonry panels, despite the use of a low reinforcement ratio (in the order of 0.03% for 2 layers of FRP).

It is sensible to note the limitations of these preliminary tests. The small dimensions of the panels have already been noted, which has resulted in the ultimate capacity of the FRP being reached at relatively small deformation. The distance between anchorages would be greater in a real application, giving higher deformation capacity. It is envisaged that the masonry panel would be enclosed in a net of unbonded FRP ‘bandages’, tailored to match the deformation capacity of the elastic FRP to the crack opening in the masonry. The bandage could pass through holes made in the wall, or a mechanical fastening made to the surface of the masonry. A more refined connection between the ends of the FRP bandage would avoid the variation in deformation capacity observed in the current tests due to the primitive clamping arrangement.

## 5 CONCLUSIONS

The tests described in this paper demonstrate that unbonded FRP offers an alternative approach to bonded FRP applied for improving the in-plane shear performance masonry panels. The FRP acts as a 'bandage' that confines the surfaces of the cracked masonry and takes advantage of the frictional behaviour of the joint to provide ductility.

Unbonded FRP retains many of the benefits of bonded FRP strengthening: the installation benefits of lightweight materials are retained, it is thin (and so can be hidden within finishing layers), and there are no corrosion concerns. However, it avoids the need for adhesives and the associated surface preparation, giving health and safety benefits, environmental benefits, and giving a more reversible solution for heritage applications.

## ACKNOWLEDGMENTS

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