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SHEAR STRENGTHENING OF MASONRY PANELS WITH GFRP: PRELIMINARY EXPERIMENTAL RESULTS

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SUMMARY

This paper describes an experimental investigation of masonry strengthened with GFRP. Square masonry walls of clay or concrete bricks were built, and strengthened using sheet GFRP (applied by the wet lay-up method). These specimens were tested under a combination of in-plane shear load, and vertical prestress (representing the weight of the building above). Preliminary results and experimental observations are presented, and their implications discussed.

Il presente lavoro descrive un programma sperimentale effettuato su murature rinforzate con GFRP. Per effettuare le prove sono stati costruiti muri quadrati con mattoni di laterizio o di calcestruzzo, successivamente rinforzati con tessuto di fibra di vetro, applicato a secco sullo strato di resina. I campioni sono stati portati fino a rottura sotto l'azione di uno sforzo tagliante agente nel piano della muratura, combinato con un carico verticale ottenuto mediante presollecitazione della muratura, tale da simulare il peso della struttura sovrastante. Di seguito vengono presentati e discussi i risultati delle prove sperimentali.

INTRODUCTION

Fibre-reinforced-polymer (FRP) reinforcement has considerable potential for repairing and strengthening masonry structures. FRP strengthening systems have high strength-to-weight and stiffness-to-weight ratios; they are corrosion resistant; are easily applied to an existing structure; and can be tailored to suit a particular application. Further details are given by (for example) Triantafillou [1].

A variety of approaches have been developed for applying FRP reinforcement to masonry:

- Sheet FRP can be applied over the whole surface of the masonry. The reinforcement is typically supplied as a flexible mat (comprising only the fibres), which is easy to position and cut to size. The reinforcement is attached to the wall using an adhesive resin [2,3,4].

- Rather than covering the whole surface of the masonry, sheet FRP can be applied locally to regions particularly susceptible to damage [4].

- Strips of pre-formed FRP reinforcement (usually with unidirectional fibres) can also be applied to the surface of the masonry. These can be arranged in an external truss, tailored to suit the application [4].

A masonry wall will typically be subjected to three principal actions: out-of-plane bending, in-plane bending, and in-plane shear. These actions are accompanied by a vertical axial load, due to the self-weight of the building above the specimen [1].

The current work studies the in-plane shear response of masonry reinforced with sheet glass-fibre-reinforced-polymer (GFRP), shown schematically in *figure 1*.

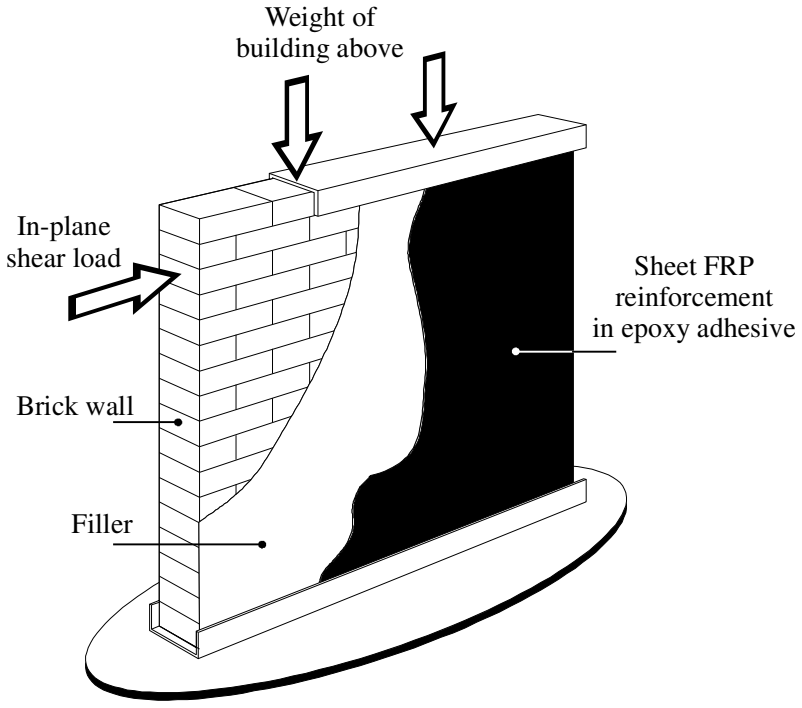


Figure 1 - In-plane shear strengthening using sheet GFRP

The square specimen represents a panel taken from the wall of a building. This approach is similar to that adopted by modern analysis techniques for masonry. These techniques model the constitutive response and failure of a masonry panel (the macro-response), rather than considering the interaction of the bricks and mortar in detail (the micro-response) [5].

EXPERIMENTAL SETUP

Specimen description

Six masonry specimens were tested, the details of which are recorded in *table 1*.

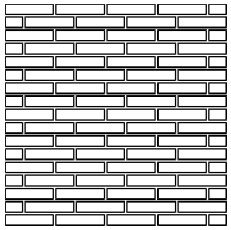
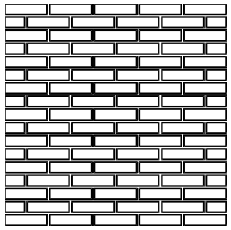
	Clay	**Concrete**
Specimen details	1 unreinforced wall: *"Clay 1"* 2 reinforced walls: *"Clay 2, Clay 3"*	1 unreinforced wall: *"Concrete 1"* 2 reinforced walls: *"Concrete 2, Concrete 3"*
Bond pattern		
Dimensions (mm)	1260 × 1260 × 125	
Brick size (mm)	276 × 57 × 125	239 × 64 × 125
Reinforcement	Biaxial GFRP. (0° / 90°, balanced fibres). Applied parallel to base of wall.	
Reinforcing sequence	Primer ↓ Epoxy putty filler ↓ GFRP + epoxy adhesive	Cement render ↓ Primer ↓ GFRP + epoxy adhesive

Table 1 – Details of the specimens

Three specimens were constructed from concrete bricks, and three from clay bricks. Due to the different sizes of the clay and concrete bricks, slightly different bond patterns were necessary for the two different materials (as shown in *table 1*).

One specimen from each material was left unreinforced; the other two were reinforced using sheet GFRP.

Application of the GFRP reinforcement

A biaxial sheet glass-fibre reinforcement was used, with an equal number of fibres in the 0° and 90° directions. As summarised in *table 1* and indicated in *figure 1*, there were a number of stages to applying the GFRP reinforcement.

The clay walls were first thoroughly cleaned, and then primed to seal pores in the surface of the bricks and mortar (using an epoxy primer). To provide a smooth surface (and thus good adhesion of the GFRP), an epoxy putty filler layer was applied to the wall (illustrated in *figure 2*). Once this had dried, epoxy adhesive was spread on the wall, the GFRP sheet firmly attached, and the surface of the GFRP coated with a final layer of epoxy resin to ensure saturation of the fibres (shown in *figure 3*). The GFRP was firmly anchored at both the top and bottom of the specimen.

Figure 2 - Application of epoxy filler layer to clay wall

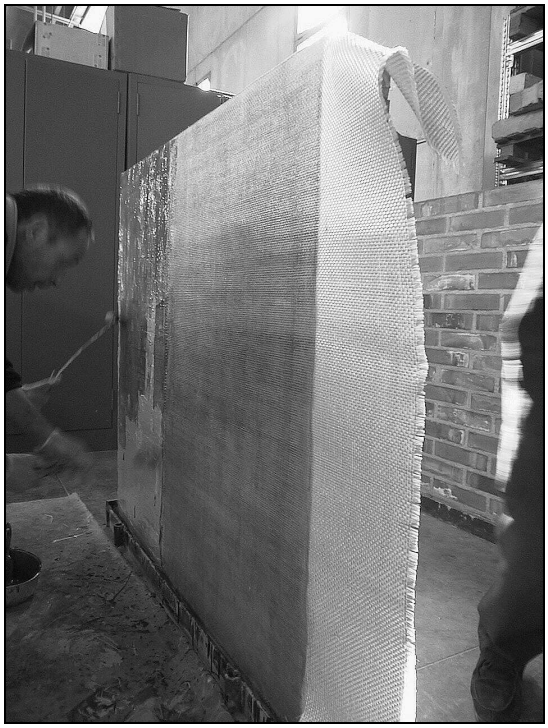


Figure 3 - Wet lay-up of glass-fibre reinforcement in epoxy resin

The concrete walls were prepared in a slightly different manner. A cement render was used as the filler layer (rather than the epoxy putty). This was sealed using the epoxy primer, and the GFRP applied to its surface by the wet lay-up process described above.

Test arrangement
The test arrangement is shown in *figures 4 & 5.*

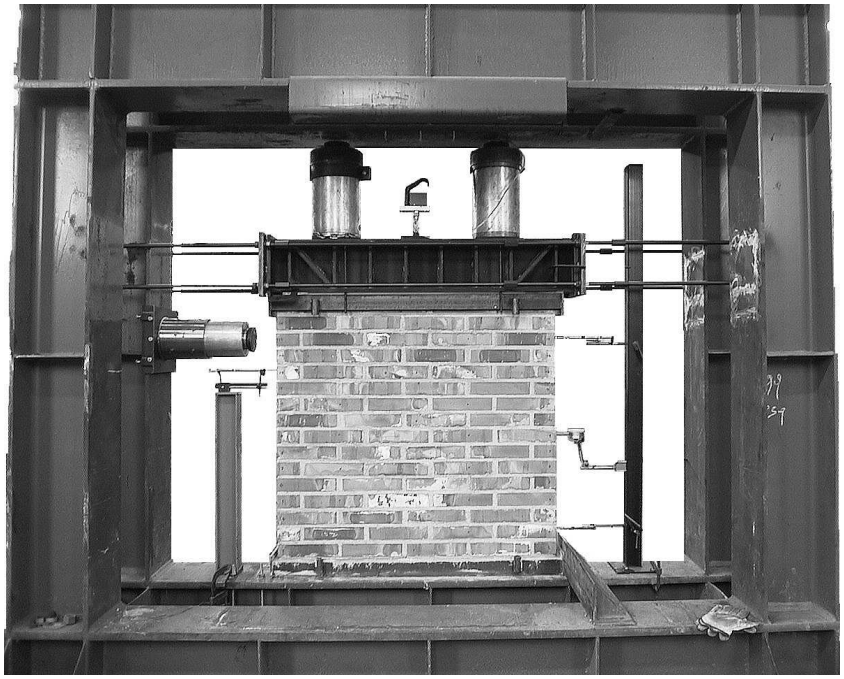


Figure 4 – Test frame

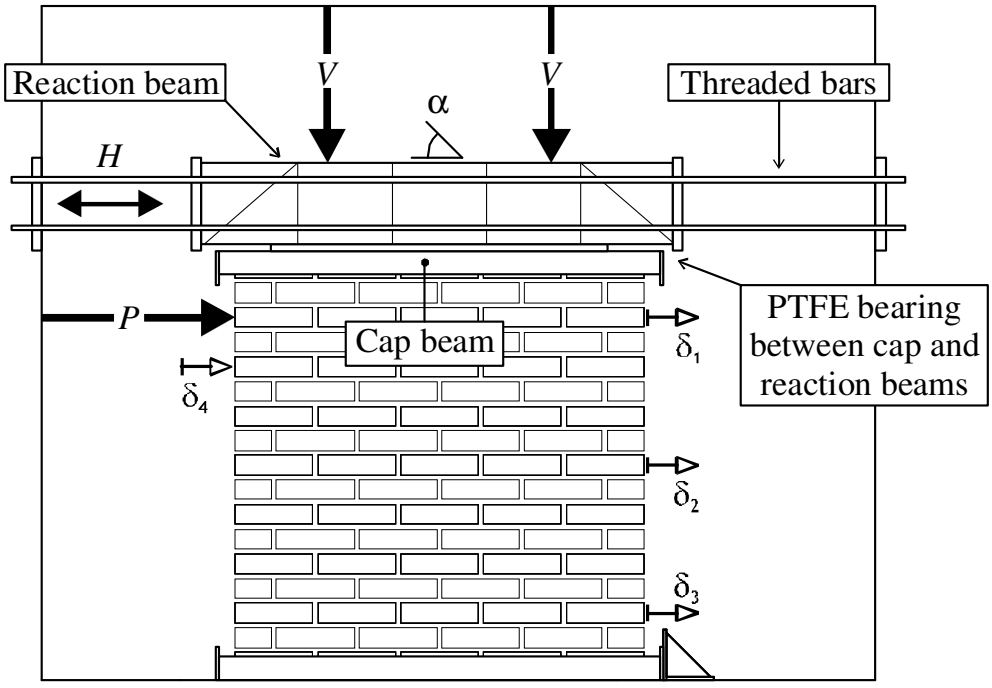


Figure 5 – Test arrangement

The vertical prestress load was applied through two connected pistons (*V*). This load was distributed across the top of the specimen by a stiff steel reaction beam (restrained horizontally by threaded steel bars), and transferred to the wall via a steel cap beam. Two sheets of polytetrafluoroethylene (PTFE) separated the reaction and cap beams, allowing the cap beam to slide horizontally relative to the reaction beam.

Shear load was applied to the wall by a horizontal piston (*P*). To assess the proportion of this load carried across the PTFE joint by friction, the horizontal force acting on the reaction beam was measured by means of four strain gauges (*H*).

Figures 4 & 5 also show other instrumentation used in the tests:-

- Four displacement transducers (LVDTs) were used to measure horizontal deflections in the plane of the wall (δ_1, δ_2, δ_3, δ_4).

- Rotation of the reaction beam (assumed equal to the top of the wall) was recorded using an angular transducer (α).

- Strain gauges were applied to the GFRP surface, the position of which depended on the test specimen.

(Due to a limit of 8 channels on the data-logging equipment, the middle displacement gauge, δ_2, was sometimes omitted).

RESULTS

Loading sequence

A vertical prestress (*V*) of 100kN was initially applied to the wall. The horizontal load (*P*) was then increased in steps of 10kN. Once 50kN was reached, after each subsequent loading increment, *P* was reduced to 40kN to allow the specimen to be inspected.

(Note that it was not possible to maintain a constant vertical prestress. The vertical prestress increased with the horizontal load).

Failure of the masonry components

Figures 6 to *9* show the unreinforced clay and concrete walls, and reinforced clay and concrete walls after testing (in that order). The cracks have been highlighted in these figures. (Note that some of the photographs have been mirrored to ensure a consistent view of the loading arrangement).

Failure occurred in the mortar by a combination of (i) tensile failure, (ii) shear failure and (iii) compressive crushing. In the bricks, only tensile failure was observed, since the compressive strength of the bricks is much greater than that of the mortar.

Except for the unreinforced clay wall, the masonry failed by rapid propagation of a diagonal crack across the specimen. Failure of the unreinforced clay wall occurred along a near-horizontal crack at the base of the wall, and was dominated by sliding along the mortar joint.

Figure 6 – Unreinforced clay (clay 1)

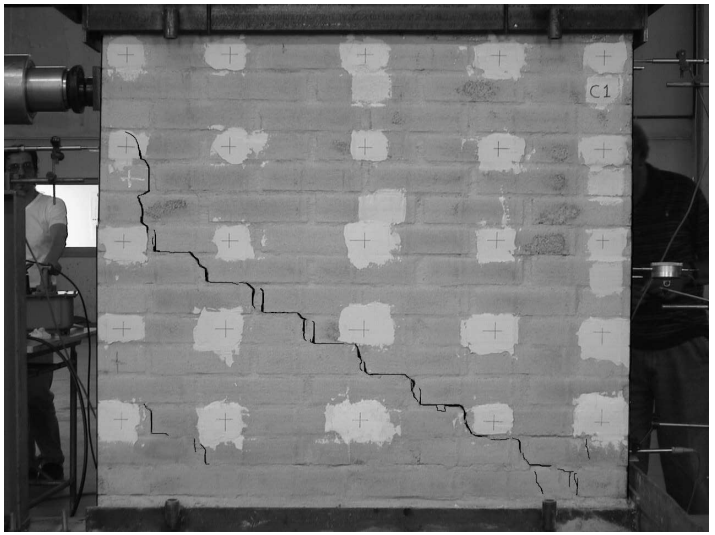


Figure 7 – Unreinforced concrete (concrete 1)

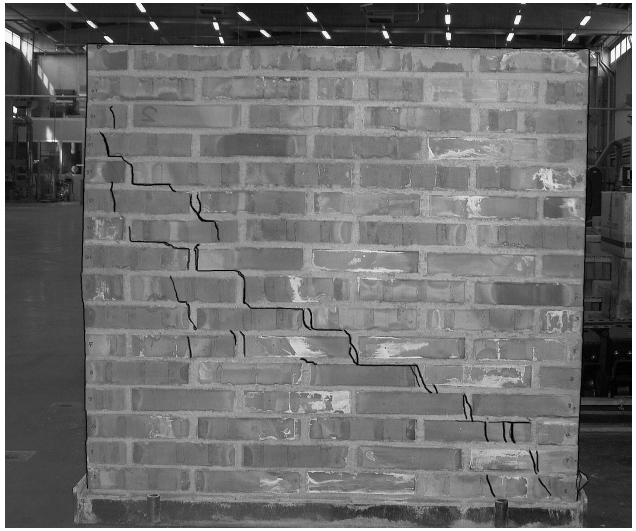


Figure 8 – Reinforced clay (clay 2) – mirrored

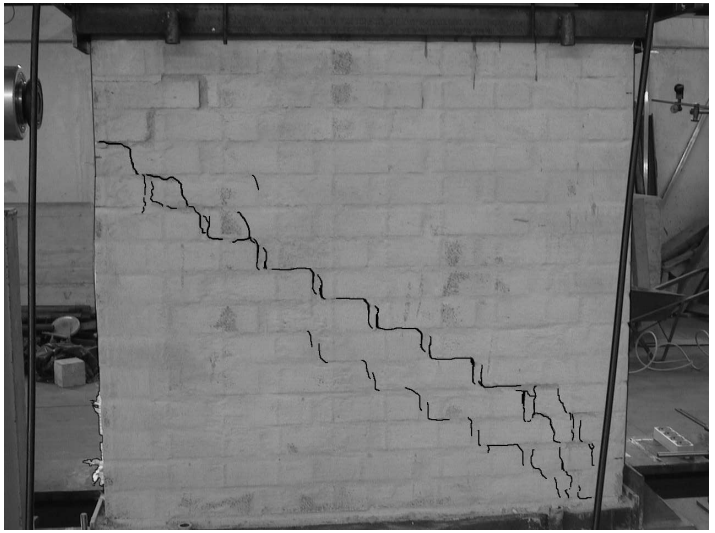


Figure 9 – Reinforced concrete (concrete 3) – mirrored

In the walls strengthened with GFRP, failure was not restricted to a single diagonal crack: the cracking was slightly more distributed, giving a band of cracking.

Failure of the GFRP strengthening

Failure of the GFRP strengthening did not occur in the GFRP itself, but was characterised by de-bonding of the reinforcement from the surface of the wall. Initially, small regions of local de-bonding occurred near the load application point and the reaction point at the opposite corner of the wall. At the ultimate load, sudden de-bonding occurred over a large portion of the specimen, roughly along the diagonal from the load application point to the opposite corner.

Figures 10 & 11 show the de-bonded reinforcement after a test, while *figure 12* shows the extent of de-bonding. (This was mapped by tapping the surface of the wall and noting where the reinforcement sounded hollow).

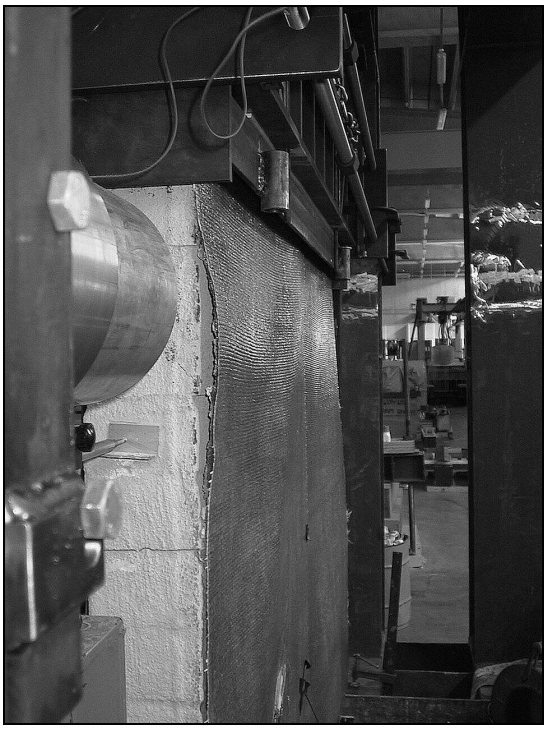


Figure 10 – De-bonding at loading point (concrete 2)

Figure 11 – De-bonding at opposite side to loading point (concrete 2)

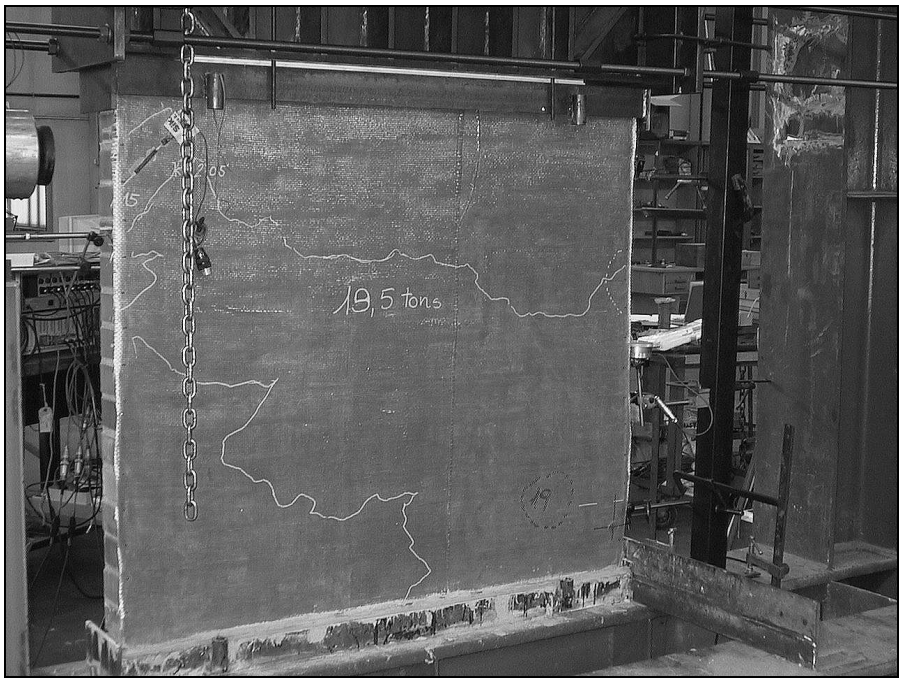


Figure 12 – Extent of de-bonded region (clay 2).

Separation of the GFRP strengthening from the masonry was not due to failure of the epoxy adhesives. In the clay walls, failure occurred beneath the surface of the brick (*Figure 13*). In the concrete walls, failure occurred between the cement render and the bricks (*Figure 14*).

Figure 13 – De-bonding of clay wall

Figure 14 – De-bonding of concrete wall

Load-deflection responses

Figure 15 shows the load-deflection responses of the clay specimens, while *figure 16* gives the same information for the concrete walls. For clarity, only one unload-reload loop has been shown in the figure for each test.

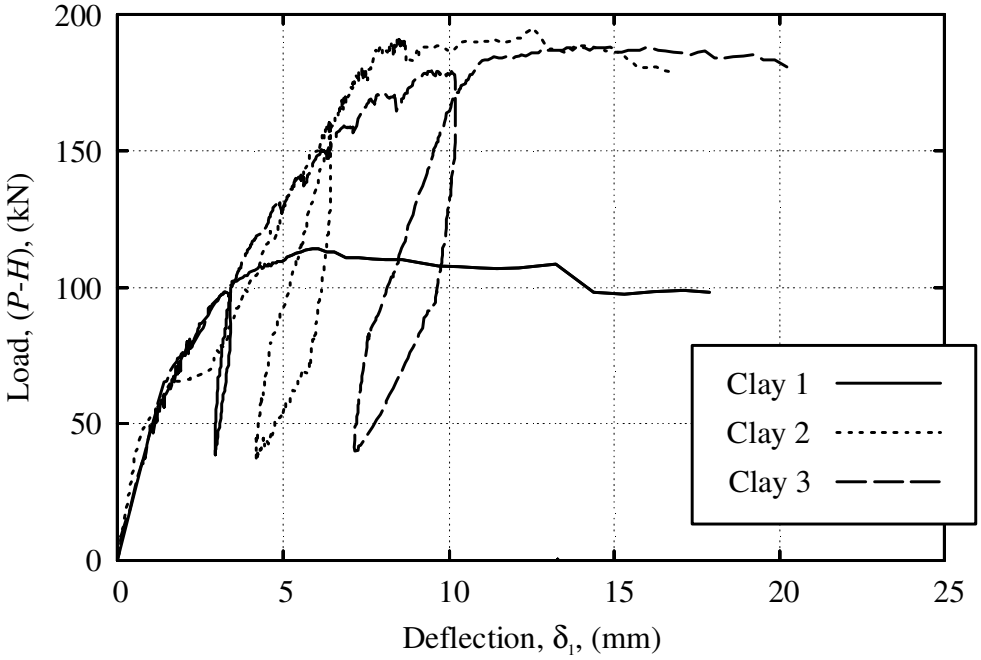


Figure 15 – Load-deflection response of the clay specimens

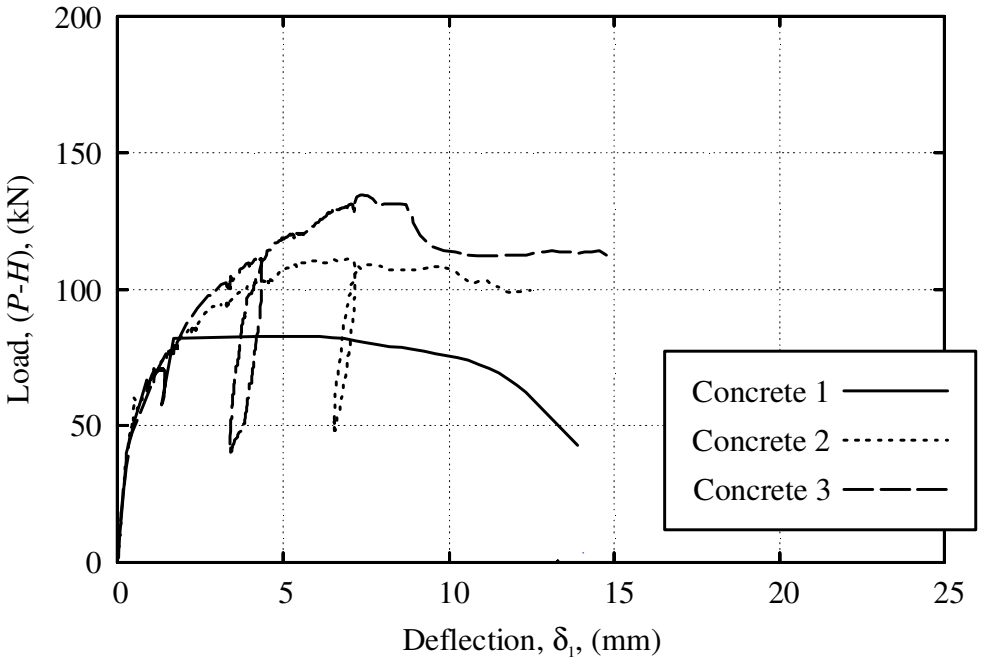


Figure 16 – Load-deflection response of the concrete specimens

The figures plot the load carried through the wall, accounting for the horizontal load carried through the PTFE joint (*P-H*). The horizontal deflection was measured at the same level as the load application point, on the opposite side of the wall (δ_1 in *figure 5*).

Strengthening the clay walls with GFRP increased the ultimate load from approximately 115kN to 190kN. For the concrete walls, the ultimate load increased from 80kN to 110kN (for specimen concrete 2), and 130kN (for specimen concrete 3).

The comparatively low failure load of the concrete walls (relative to the clay walls) is probably due to use of an inappropriate mortar. The concrete bricks were very porous, and consequently the mortar dried before it had fully cured.

DISCUSSION

The experimental results presented above are largely qualitative manner, since (at the time of writing), analysis of the data has not been completed. However, some preliminary observations are possible.

Applying GFRP with balanced 0° / 90° fibres is an effective method of increasing the ultimate strength of masonry. For both clay specimens, and specimen concrete 3 an increase in the ultimate load of approximately 65% was observed. However, for specimen concrete 2, the increase in ultimate load was only 38%.

Failure of the GFRP-masonry interface is brittle. Stress redistribution is not possible within a brittle specimen, so that after failure is initiated rapid collapse follows. Thus, failure of GFRP-strengthened masonry is very dependent on local stress concentrations, and on the boundary conditions applied to the masonry panel.

In the present tests, there are stress concentrations at the application point of the horizontal load, and in the opposite corner of the specimen (where the horizontal load is reacted). Stress concentrations may also occur due to defects in the GFRP-masonry bond. It is suggested that the poor performance of specimen concrete 2 is related to the sensitivity of GFRP reinforced masonry to stress concentrations.

Strengthening should not be considered solely in terms of increased failure load. A successful strengthening system will also be ductile. This is particularly important in seismic design where gradual, sustained, energy dissipation is required during cyclic loading.

In the present tests (see, in particular, *figure 15*), there is a plateau at the peak load, indicative of ductility. From observations made during the tests, this plateau is due to a transformation in the load-carrying mechanism in the wall. Prior to de-bonding, load is carried by composite action of the masonry and GFRP. After de-bonding, tension cannot be carried across the diagonally-cracked masonry, and a truss mechanism acts, in which the GFRP forms a diagonal tensile member. The load carried by the truss mechanism will depend on the unbonded length of reinforcement. Note that the transformation to a truss mechanism involves de-bonding of the GFRP, and consequently a sudden release of a large amount of energy (which is not desirable).

In a real application, the load plateau will be difficult to guarantee. In particular, good anchorage is essential at the top and bottom of the strengthening. (Note that Schwegler [4] has proposed a more controllable truss strengthening system).

CONCLUSIONS

Sheet GFRP is easily applied to masonry as strengthening. It increases the failure load of masonry subjected to in-plane shear loading. The failure load is sensitive to stress concentrations and the boundary conditions of the specific wall.

Failure is by brittle de-bonding of the GFRP-strengthening from the masonry, governed by the weakest component in the masonry-GFRP interface.

There is considerable potential for intelligent use of *fibre-reinforced polymers (FRPs)* for strengthening. However, further work is required, in particular regarding the ductility of the specimen, and its response to cycling-loading.

ACKNOWLEDGEMENTS

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