LABORATORY TESTING OF A VARIETY OF STRENGTHENING SOLUTIONS FOR BRICK MASONRY WALL PANELS

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SUMMARY

Six brick walls were strengthened by various methods and tested in-plane under a slow cyclic loading. For the most promising strengthening methods, cost comparisons are made, and design strengths are recommended which accord with the New Zealand Loadings Code (Ref. 1).

INTRODUCTION

Most buildings constructed in New Zealand up until the early 1930s consisted of unreinforced clay brick walls. Rapid change in materials used occurred following a large earthquake in Napier, 1931, when about 200 people died. A large stock of unreinforced brick buildings still remains and local governments have power to order demolition or strengthening.

The most common method of strengthening is through the application of a reinforced, sprayed concrete layer to an interior face of walls. (Ref. 1) A thickness of up to 150 mm (6 inches) is applied and the reinforcement (rods or mesh) lapped with dowels into foundation wall and concrete ring beams. The tests reported here examine the ability of a variety of coatings to resist cyclic in-plane shear loads.

DESCRIPTION OF WALL TEST UNITS AND APPLIED LOADING

All wall units were 2.400 m (7 ft 10 in) high, measured between reinforced concrete capping-and-base-beams. The loading was applied as a reversing horizontal force at mid-height creating a point of zero moment at this location but equal top and bottom moments. The loading rig is described in Figure 1. The ratio of applied moment to shear is minimised with this system.

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Where practicable, vertical reinforcement was placed at the ends of the test units to ensure that failure in a flexural mode did not take place.

Unit SW1 and SW2 - Prestressed Walls

Brick and mortar, with properties similar to those of the pre-1930s, were used to construct these units. Prestressing of these two-wythe specimens was external to avoid the cost of drilling through bricks, and the only difference between the two specimens was that unit SW1 was prestressed to 200 kN (20 t) and SW2 to 400 kN (40 t). This prestress was kept as constant as possible during testing.

Unit SW3 - Sprayed Concrete Walls

A single layer of brick was constructed in running bond and the face against which sprayed concrete was applied was first coated with a damp-proof ("Mulseal") in four layers in accordance with the manufacturer's instructions. Figure 2 shows the reinforcing details. Epoxyed dowels to top and bottom beams were staggered in order to reduce effects of 'shadowing' during application of the sprayed concrete.

A "wet process" was used by the local contractor engaged for the operation. Ready-mixed concrete (maximum aggregate size ¼ in) was fed into a cylinder which was sealed and pressurised in order to force the mix through the delivery hose. Some slumping of the sprayed concrete was evident. A set of similarly reinforced test panels was produced for obtaining cored specimens.

Unit SW4 - GRC-Coated Wall

The overall length of the single skin brick specimen was 2.000 m (6 ft 7 in). Both faces were coated by hand plastering with Glass Reinforced Cement (GRC). Details are shown in Figure 2.

The GRC mix (Ref. 3) was developed by MWD Central Laboratories and has an acrylic emulsion base, which has several advantages:

. moist curing of the plaster coating is not required
. the bond of glass fibres to surrounding cement paste is enhanced
. adhesion between the cement paste and the brickwork (coated with damp-proof course) is improved.

Of particular importance is the expectation that the acrylic emulsion base will reduce the observed time-dependence of GRC strength by restricting the potential for growth of crystals of cement hydrate around the glass fibres, and damaging them.

Unit SW5 - FRC-Coated Wall

The "FRC" (steel-fibre reinforced concrete) coating used "enlarged end" fibres (i.e. profile similar to that of a dumbell) and overall length of 18 mm (3/4 in). These were obtained from Australian Wire Industries Ltd.

A matrix of constituent qualities similar to the GRC mix was used. An analysis of costs involved in the GRC strengthening method revealed that the steel connector at wall top and bottom contributed two thirds of the unit cost, and that a significant component of this was the cost of drilling holes in the concrete. In addition, failure of the dowel connectors in the GRC wall had been observed. For these two reasons, dowels were inclined for the FRC wall and mounted on an angle section which was connected to top and bottom beams by four D24 bars.

Unit SW6 - Ferrocement Wall

A proprietary steel mesh ('Watson mesh') was anchored to the brickwall by fire-in nails, a sand-cement plaster forced through the fine mesh to the backing brickwork and then built up to a total thickness of 20 mm. A company using this system for ferrocement work on other products was engaged to set up the mesh and apply the plaster.

RESULTS OF TESTING

Unit SW1 and SW2

For both these prestressed units considerable effort was needed to maintain the preload. This tended to drop during "push" half-cycles and rise again during "pull" half cycles. Such behaviour resulted from the development of a single full-height diagonal crack along which sliding took place. Such sliding would have been restricted by dowel action for the stressed rods if they had been contained within the brickwork.

SW3 - Sprayed Concrete Wall

The loading sequence consisted of one cycle to 0.5 mm, then to 1.0 mm, two cycles to 2 mm, then to 4 mm followed by seven cycles to 8 mm (nominal). Early in the loading sequence, cracks were observed at both sprayed concrete-concrete beam interfaces. However, most cracks at deflections up to 4 mm were diagonal, less than 0.5 mm (1/64 in) wide and clustered in the vicinity of the top corners. Upon loading repeatedly to ± 8 mm top deflection (5/16 in), a set of full height diagonal cracks developed, associated with the "pull" half-cycles. During these last cycles local separation between brickworks and sprayed concrete of up to 8 mm (5/16 in) was observed apparently extending over most of the length of the test unit. The demise of the unit was associated with dowel failure of the reinforcement of the top.

Unit SW4 - GRC-Coated Wall

The load-deflection history consisted of one cycle to 1 mm, 2 cycles to 2 mm, 4 cycles to 4 mm, 2 cycles to 6 mm and 2 cycles to 8 mm. At the first cycle of 4 mm (0.15 in) the peak loads attained both in pushing and pulling were 450 kN. First cracking was noticed at cycle 1 of pull loading at 4 mm (0.15 in). This occurred in the 14 mm GRC zone in the form of disjointed diagonal hairline cracks. The stiffness degraded markedly in the 6 mm cycles, and the maximum diagonal crack width in the 14 mm (0.55 in) GRC zone was 1.5 mm (0.06 in) in the first pull cycle increasing to 4 mm during the second pull cycle. A drastic drop in load capacity occurred during the first pull cycle at 8 mm (0.32 in), with the sudden development of a major diagonal crack in the wall. The test was terminated at this stage (Fig. 3).

Unit SW5 - FRC-Coated Wall

The loading sequence consisted of one cycle to 1 mm, 2 cycles to 2 mm, then to 4 mm and 6 mm, 8 cycles to 8 mm and 2 cycles to 12 mm. Vertical cracks at both top and bottom ends appeared during the 4 mm cycles. Diagonal cracking in both directions in the 14 mm panel developed during loading to 6 mm. About 2 mm of slip of the top beam was noticed during "push" loading to 8 mm. Cracks developed within the panel as well as in the transition zone. Nevertheless, the loops obtained were remarkably stable over the eight repetitions of cycling to 8 mm. A major diagonal crack opening up to 3 mm (1/8 in) appeared during cycling to 12 mm and during the first "pull" half cycle sudden loss of strength occurred with the growth of a major diagonal crack to 10 mm (3/8 in) wide. The peak load of about 200 kN (20 t) was attained at top displacement of 4 mm.

Unit SW6 - Ferrocement-Coated Wall

The loading sequence consisted of one cycle to 1 mm, 2 cycles to 2 mm, 4 mm and 6 mm, and 1 cycle to 8 mm. On the first cycle to 2 mm, extensive fine diagonal cracking occurred in both directions together with some flexural cracks in the end "columns". Development of slip at the interface of top beam and brickwork was evident during the first cycle to 4 mm. Separation of the plastered mesh from the top section of reinforced concrete wall ends was very prominent and was associated with extensive slip of the top beam.

DISCUSSION OF RESULTS

Figure 4 compares results of the six specimens by superposition of curves which envelope each set of hysteresis loops. The curves are fitted by eye through peaks associated with the second or subsequent cycles at respective deflection maxima. It is clear that unit SW5 is the strongest of the specimens tested.

The performance of the prestressed walls, Units SW1 and SW2, was not impressive. However, because restraint against sliding by dowel action could not develop and because rotation of the wall specimen resulted from its short length, no firm conclusions can be drawn from these tests about the general applicability of prestressing as a strengthening solution.

The ferrocement-coated wall (Unit SW6) was also not very strong. However, the method of applying the coating did not enhance the bond to brickwork. Further testing with the mesh pressed into an initial coating of mortar would be needed to confirm the viability of this procedure.

The remaining three solutions - sprayed concrete (Unit SW3), GRC (Unit SW4) and FRC (Unit SW5) are, at this stage, the most promising forms of solution for in-plane strengthening of brickwork. The sprayed concrete approach is almost the sole method of strengthening currently being used in New Zealand. However, it is clear from Figure 4 that thin coatings can produce stronger walls. It is considered that both faces of brickwork should be coated to ensure stability for both in-plane (especially for one or two-wythe brickwork) and out-of-plane loading.

Design Loadings

Sprayed concrete coatings are designed for the most part as for reinforced concrete. However, design criteria for the connections to top and bottom beam are unclear. It is probable that by improving the dowel design, the strength of the unit, as well as its energy dissipating capability, would have been improved.

The New Zealand Loadings Code (Ref. 2) proposes a criterion which can be used to determine design seismic loading. Although the criterion is discussed in the context of frame structures, it can be inferred that the design seismic-induced deflection is that at which, after four cycles to full elasto-plastic deflection the design ("yield") strength has not reduced by more than 30%. Further, the design load required can be reduced to half of that under which the structure would respond elastically. This reflects the "limited ductility" (Ref. 2) available in shear walls. For this situation, a criterion between the "equal displacement" and "equal energy" rules indicates that the maximum deflection is about 1.5 times that at design load. Hence a deflection can be obtained from experimental load-deflection curves at two thirds of which, strength reduction is less than 30% after four cycles. For the test specimens where applicable, further reduction in the load value needs to be made to account for:

- capacity reduction factor ($\phi = 0.85$)
- portion of horizontal load resisted by vertical end segments
- 50% overstrength already implied in the loadings code (Ref. 2)

Further details are given in Reference 3 and the design strengths thus determined are given in Table 1. These are not "universal" figures but depend on wall reinforcing (for sprayed concrete), thickness of coating (FRC and GRC) and details of connection to top and bottom beam. The method is fairly crude as the design elasto-plastic deflection value is not known during testing. Hence four cycles to the value deduced from the hysteresis loops should be executed in a test of a second specimen to confirm the deduced design load.

Finite element analyses of various lengths of thin coated walls were carried out (Ref. 3). These indicated that in order to ensure that principal tensile stresses at the vertical edges did not exceed those within the body of the wall, the ratio of height of point of contraflexure to wall length should not exceed about 0.25. Undesirable progressive failure by edge tearing would otherwise have to be prevented by special vertical end reinforcement in thickened bands.

Relative Costs

Unit rates for sprayed concrete in building strengthening contracts have fallen considerably over the past 2 years as the industry has gained confidence in the method. The GRC mix is now able to be purchased bagged and has been used in a minor way on one strengthening contract. Unit rates assessed for the hand plastering of GRC and FRC are still somewhat uncertain, therefore.

Table 1 gives the best estimate of cost available at the present time for the three solutions (column (a)). The costs of top and bottom connectors is included and the wall height is taken as 3.5 m (11 ft 6 in).

Table 1 : Design Strengths and Costs

		(a)	(b)
Sprayed Concrete (1 face)	49 kN/m (1.5 t/ft)	$458/m	$9.35/kN
GRC (2 faces)	107 kN/m (3.3 t/ft)	$658/m	$6.15/kN
FRC (1 face)	106 kN/m (3.2 t/ft)	$462/m	$4.36/kN

This comparison is valid provided that coating in-plane shear strength does not govern the quantity. When strength governs, however, a correction must be applied using the design loads proposed earlier. Then the cost per unit strength (1 kN = 0.1 t) is as shown in column (b) of Table 1. It is seen that sprayed concrete is less economical than GRC or FRC on a strength basis but compares favourably on a unit area basis.

CONCLUSIONS

A variety of cementitious coatings are possible for the in-plane strengthening of unreinforced brick masonry walls against seismic loading. Thin fibre reinforced coatings, even when application is by hand plastering, are very competitive economically with the more common reinforced sprayed concrete solution.

ACKNOWLEDGEMENT

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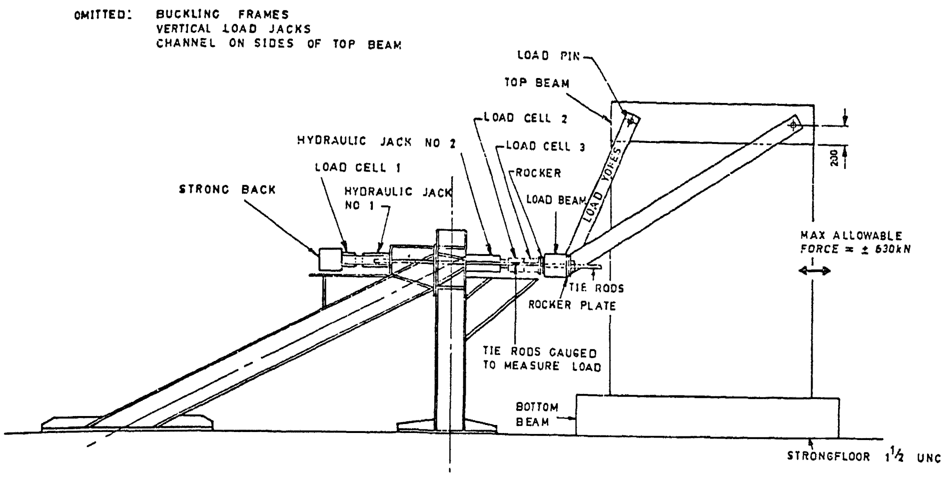
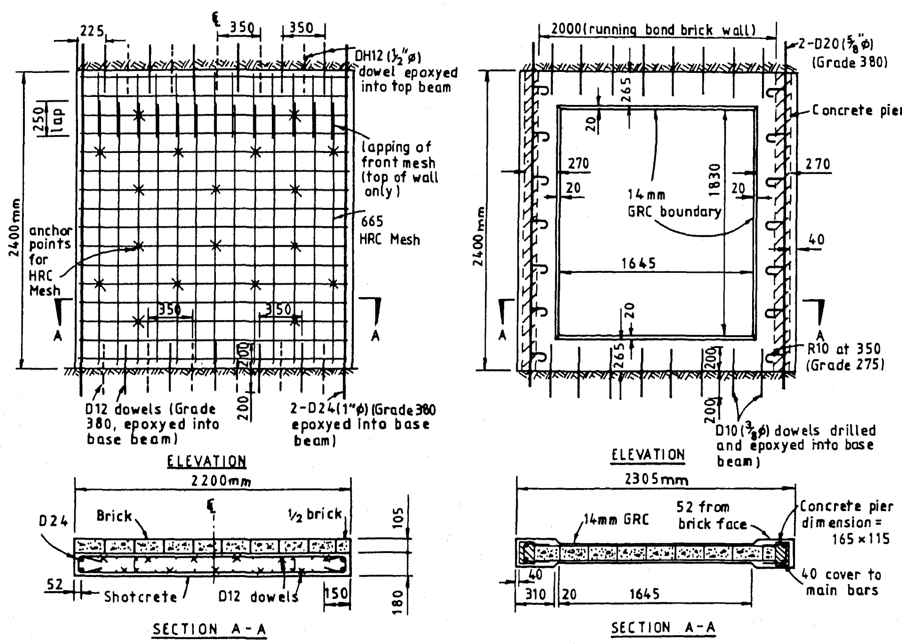


Fig. 1. Load - Reaction System.



(a) Unit SW3: Sprayed Concrete

(b) Unit SW4: GRC

Fig.2. Two of the walls tested

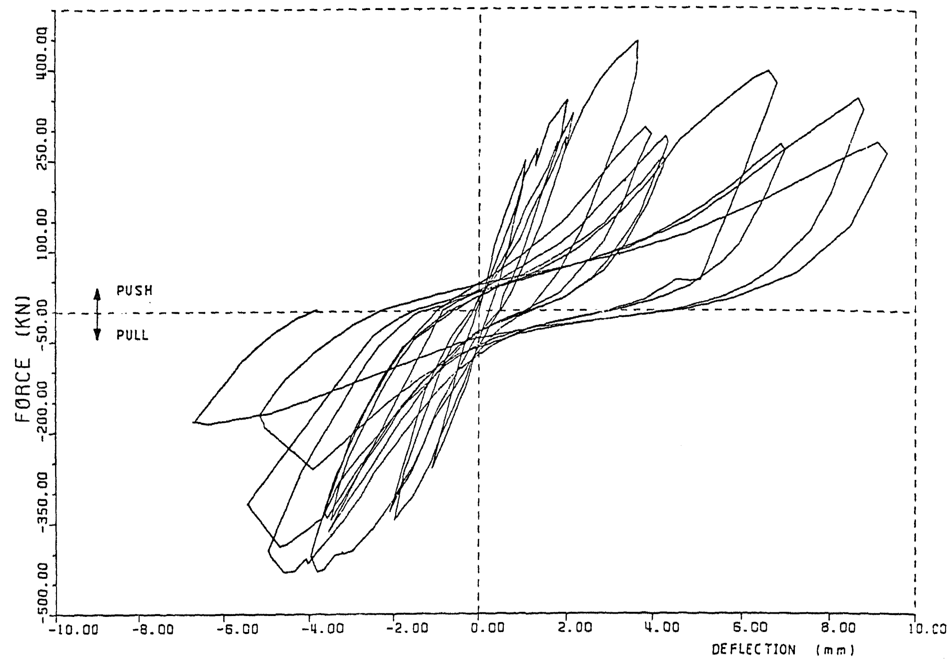


Fig. 3. Load-deflection history for GRC-coated wall.

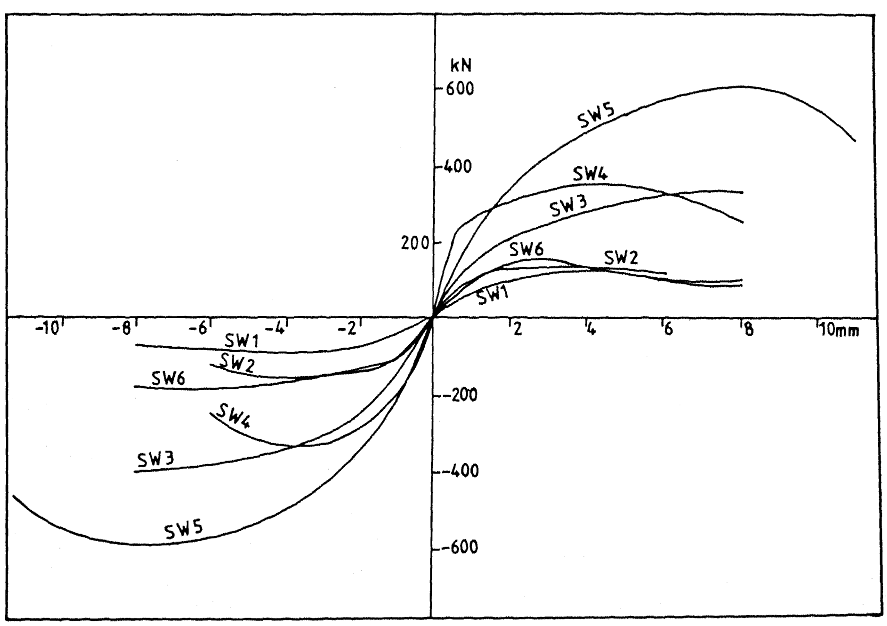


Fig. 4. Envelope of load-deflection histories for all specimens.