SHOTCRETE RETROFIT FOR UNREINFORCED BRICK MASONRY

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SUMMARY

Fifteen 3 ft. x 3 ft. and 4 ft. x 4 ft. brick masonry panels were constructed, then were retrofit with a 3 1/2-inch layer of reinforced shotcrete. In-plane tests showed that a saturated, wet brick surface provided adequate bond to develop the full composite strength of the panels. Dowels did not improve the composite behavior or bond of two-wythe brick-shotcrete panels. Shear strength and ductility primarily were dependent on the shotcrete plus reinforcement alone.

INTRODUCTION

Purpose and Scope

The purpose of the research was to investigate the most common retrofit technique used on unreinforced brick masonry walls -- a layer of reinforced shotcrete applied to one surface. Of specific interest was the in-plane, composite behavior of the brick-shotcrete structure and the quality of the brick-shotcrete bond.

Seventeen brick panels were constructed; a 3½ inch layer of shotcrete was placed on fifteen. They were tested under a single, static reversed cycle load applied across their diagonal. Nine single wythe 3 ft. x 3 ft. panels were used to investigate various brick surface bond treatments, dry, wet or epoxy coated. Six double wythe, 4 ft. x 4 ft. panels were used to determine whether dowels enhanced the connection bond between the masonry and shotcrete. One single wythe 3 ft. x 3 ft. panel and one double wythe 4 ft. x 4 ft. panel were tested without a shotcrete surface.

Background

Many unreinforced brick masonry walls, both load-bearing and architectural, have been strengthened to provide earthquake resistance by applying a 3-inch or thicker layer of shotcrete to either the outside or inside surface of the wall. Often the strengthening analysis assumes that the masonry has zero lateral strength and that the new reinforced shotcrete element must resist all seismic forces. The possible composite response is not considered. For retrofit of school buildings, California state engineers considered that the brick-shotcrete bond provided by a

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wet, saturated brick surface is sufficient to hold the brick masonry intact during an earthquake; dowels anchored into the brick and hooked into the shotcrete are unnecessary. Many other engineers for retrofit of public and private buildings have required dowels, #3, #4 and larger bars, epoxied or cement grouted into holes drilled into the masonry; the holes are spaced 3 ft. to 4 ft. on centers. Some engineers believe that a bonding agent like epoxy is required to be painted or sprayed on the brick so that adequate brick-shotcrete bond is developed. There is no consensus on brick-to-shotcrete bonding and the need for dowels.

EXPERIMENTAL MODELS

Table 1 lists the model panels together with experimental results. All panels were built using old, solid molded bricks which were retrieved from the demoliton of a 54 year old building. Masons constructed the panels outside using a mortar typical of that used in the 1930's: 1 part lime, 1 part portland cement, and 6 parts sand by volume. Mortar cube strength (m_o) averaged 460 psi. Prisms yielded a masonry compressive strength (f_m') of 1630 psi.

The shotcrete mix was one part Type I portland cement to three parts sand by volume. Cores, 1.4-inch diameter and 2.8-inch long, were taken from several panels about 90 days after shotcreting. The adjusted compressive strength (f_c') averaged 6900 psi. The exact thickness of each shotcrete layer is given in Table 1; the nominal, average thickness was $3\frac{1}{2}$-inches. The shotcrete in each panel, except panels 2WO-1 and 2WO-2, was reinforced with a welded wire fabric (wwf) of W4xW4x6x6, W4 plain wire on 6-inch centers each way. This wire provided a reinforcement ratio of 0.0019. The wire yield stress (f_y) was 40,500 psi; the ultimate stress was 42,600 psi.

The D, E, and W panels were built of a single wythe and measured 3 ft. x 3 ft. Panels designated 2W were built with two wythes of brick using header bricks each sixth course. These two-wythe panels measured 4 ft. x 4 ft. Four #3 bar dowels were epoxy bonded into the two-wythe panels 2W4-1 and 2W4-2 at 32-inch spacing each way; nine #3 bar dowels were bonded into 2W9-1 and 2W9-2 at 16-inch spacing each way. Holes 3/4-inch diameter were drilled through one wythe and half-way into the second; they were cleaned with a water jet. A gel-like epoxy injected into the hole bonded the #3 bars. The free end of the dowels had a 90^o hook which anchored them into the shotcrete.

In order to study the effects of surface treatment, bricks of panels D1, D2 and D3 were left dry prior to shotcreting; bricks of E1, E2 and E3 were painted with a low viscosity epoxy (Sikastix 370) about 10 minutes prior to shotcreting; bricks of W1, W2 and W3 were wetted with water for a period of 6 hours prior to shotcreting, though the brick surface was only damp when the concrete was placed. The bricks of all two-wythe panels were wetted for periods of 4 to 6 hours prior to shotcreting. Figure 1 shows the panel construction.

IN-PLANE TESTS AND RESULTS

Each panel was tested by statically applying a compressive load across its diagonal as shown in Figure 2. After the ultimate load was attained, increasing deflections were continued until the load dropped to about one-half the ultimate. The load then was decreased to zero, the panel rotated 90°, and compressive load applied across the other diagonal. This single cycle test gave load-deflection hysteresis loops which represent an envelope for cyclic response. The center of the diagonal load was applied at the brick-shotcrete interface in order to produce maximum tension across the interface. This diagonal load test was similar to that recommended by the ASTM E519-74 diagonal tension (shear) test (Ref. 1). Hysteresis plots are shown in Figures 3 and 4.

The panels were instrumented with 24-inch long mechanical strain gages along each diagonal on both sides. Out-of-plane deformations were taken on each side to determine delamination of the brick and shotcrete and to measure the flexure of the panels.

Strength, Cracking

The shotcrete greatly increased the strength of the unreinforced brick panels. Table 1 lists the diagonal loads at observed first cracking of the brick and shotcrete plus the ultimate load. For each panel the top numbers are for the first half-cycle; the bottom are for the second half cycle. The two panels without shotcrete were C1, single wythe, 3 ft. x 3 ft., and C2 with two wythes, 4 ft. x 4 ft. Upon first cracking each collapsed; reversed cycle loading was impossible. Four other plain brick panels were constructed, but they fell apart as they were placed in the test machine. The mortar-brick tensile strength was near zero.

Cracking parallel to the loaded diagonal occurred in the brick and shotcrete at about the same load. Considerable flexure was noted; the brick face showed greater compressive strains than the shotcrete. In all single wythe specimens, the masonry cracked diagonally through the bricks. In the two-wythe panels, the outer wythe cracked along head and bed joints. Inspection after testing showed that the interior wythe cracked through the bricks. The shotcrete caused the wythe to which it was bonded to develop its full shear capacity.

Panels reinforced with the welded wire fabric (wwf) showed significant increase in strength after first cracking and large inelastic deflection capacity compared to C1 and C2. Panels 2WO-1 and 2WO-2 without wwf showed no post cracking strength. The shotcrete plus reinforcement permitted the panels to deflect inelastically and to remain intact even after the full reversed cycle loading. Cracking and ultimate strength under the reversed load averaged 40 percent lower than under the first half cycle.

Surface Treatment

Whether the brick surface was dry, epoxy coated, or wet did not affect significantly the cracking or ultimate strength of panels D, E and

W. After the loading cycle, the brick face of all panels was hammered to knock bricks from the shotcrete so the interface could be viewed and the extent of delamination determined. Actual bond separation occurred over 40 percent of the surface area of the dry (D) panels, over 30 percent of the W, and over 10 percent of the E. In the dry and wetted panels, lamination cracks parallel to the interface were observed within the brick and within shotcrete over 30 percent of surface area. The greater in-plane cracking of the W panels compared to the E did not alter the strength or deformation response. The E and W panels showed somewhat greater inelastic deformation and load carrying capacity than the D specimens.

Dowels, One and Two-Wythe Panels

The hysteresis curves demonstrated that the load-strain response of the panels with two brick wythes was similar to those for one wythe panels; the 4 ft. x 4 ft., two-wythe panels showed somewhat greater load capacity than the 3 ft. x 3 ft. panels. That the outer wythe cracked along mortar joints and the inner wythe cracked diagonally through the bricks did not significantly alter the general load-strain response. Panels 2WO-1 and 2WO-2, which had no reinforcement, showed much more brittle response than all other shotcreted panels.

Dowels did not affect the composite behavior. Panels with no dowels, 4 dowels (spaced 32 inches on center) and 9 dowels (spaced 16 inches on center) showed the same cracking and deformation response, except for differences directly attributable to absence of reinforcement. The outer wythe of brick did not delaminate from the inner wythe in any panel. The header bricks apparently joined the two wythes. The ends of the headers remained well bonded to the shotcrete. After the complete load cycle, dowels remained firmly bonded in both wythes.

Much less brick-shotcrete bond failure and laminar cracking in the brick and shotcrete were observed in the 4 ft., 2W panels than in the 3 ft., W panels even though the wetted surface condition was the same. The diagonal cracking patterns in the shotcrete were different between the two panel sizes. A single corner-to-corner crack occurred in the 4 ft. panels while typically two diagonal cracks, 4 inches on each side of the centerline, occurred in the 3 ft. panels. The 3 ft. panels cracked more extensively which may account for the greater inplane cracking.

DISCUSSION

A method for calculation of principal tensile stresses was given by Yokel and Fattal (Ref. 2) as $f_t = 0.7336*P/2*b*t$, where f_t is the principal tensile stress, P is the diagonal load, b is the panel width and t is the thickness. Flexural and strain analysis of the panels showed that the diagonal elastic modulus of the bricks was 1/32 that of the shotcrete. A transformed section analysis plus application of the Yokel-Fattal equation gave average cracking tensile stresses in the brick and shotcrete for each panel as listed in Table 1. The mean principle cracking stresses are given below ($\sqrt{f'_c}$ and $\sqrt{f'_m}$ are in psi):

Panel Size	Shotcrete		Brick Masonry	
	1st Half Cycle	2nd Half Cycle	1st Half Cycle	2nd Half Cycle
3ft.x3ft.	5.0 $\sqrt{f_c'}$	2.0 $\sqrt{f_c'}$	.42 $\sqrt{f_m'}$	.21 $\sqrt{f_m'}$
4ft.x4ft.	3.9 $\sqrt{f_c'}$	2.4 $\sqrt{f_c'}$	.33 $\sqrt{f_m'}$	.21 $\sqrt{f_m'}$

The above shows that the 40 percent to 60 percent reduction in strength during reversed loading certainly should be considered in evaluating the composite strength of the retrofit structure.

The strength provided by the wwf reinforcement was calculated by assuming that all reinforcement crossing the diagonal crack was yielding; so, the tensile strength, $A_s f_y$, for the 3 ft. panels was 13.8 kips while that for the 4 ft. panels was 22.6 kips. Simple addition of the material cracking strengths plus the reinforcement yield strengths gave a P value less than the ultimate strength of each panel based on the Yokel-Fattal relation.

CONCLUSIONS AND RECOMMENDATIONS

Application of a layer of reinforced shotcrete to unreinforced brick masonry panels was shown to be an effective method for greatly increasing the in-plane diagonal strength plus providing reversed cycle and inelastic deflection capacity. Full composite behavior was developed regardless of brick surface treatment; although a saturated brick, wetted surface is recommended. Epoxy treatment appears unnecessary. Dowels epoxy bonded into drilled holes did not improve the composite panel response or the brick-shotcrete bonding; header bricks satisfactorily joined the wythes of existing masonry panels. Therefore placement of dowels for seismic retrofit of masonry walls does not appear to be mandatory. The in-plane strength of the retrofit panels principally resulted from the shotcrete. The current practice of calculating strength by adding the shear capacity of the shotcrete plus that of the reinforcement without considering the masonry strength satisfactorily predicts the panel ultimate strength and is recommended.

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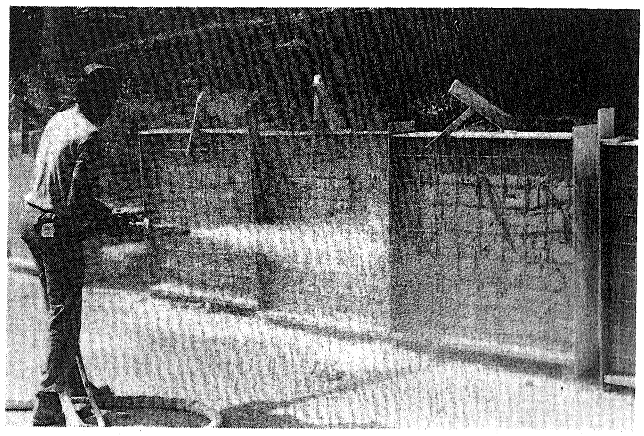

Figure 1. Shotcreting Double Wythe Panels

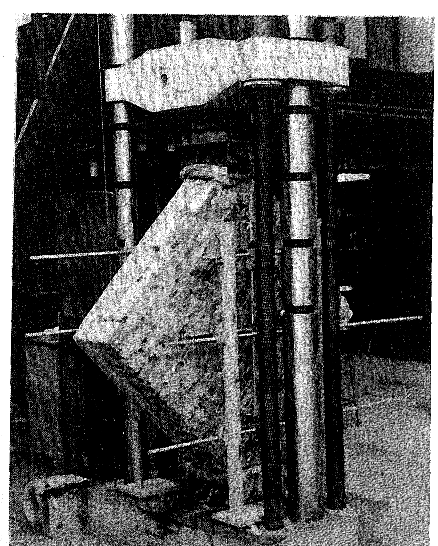

Figure 2. Diagonal Load Test of 2W Panel

Table 1. Brick-Shotcrete Panels and Test Results

Panel	Brick Surface	Shotcrete thickness (inches)	Brick Cracking Load (kips)	Shotcrete Cracking Load (kips)	Ultimate Load (kips)	Brick tensile stress (psi)	Shotcrete tensile stress (psi)
C1(a)	--	0.	6.2	--	6.2	24	
			--		--		
C2(b)	--	0.	18.0	--	18.0	26	
			--		--		
D1(a)	dry	3.1	106.5	116.7	121.8	18	496
			50.7	50.7	84.2	9	151
D2(a)	dry	3.8	121.7	121.7	147.6	17	427
			50.7	50.7	82.2	7	135
D3(a)	dry	3.4	121.7	126.8	131.9	18	472
			81.2	81.2	111.6	12	235
E1(a)	epoxy	3.1	91.3	119.7	121.8	17	485
			50.9	50.7	103.5	6	180
E2(a)	epoxy	3.8	101.4	101.5	133.9	14	314
			91.3	71.0	104.5	13	155
E3(a)	epoxy	3.8	109.0	109.0	138.0	14	357
			45.7	45.7	100.4	6	113
W1(a)	wet	3.4	108.5	108.5	142.0	16	383
			71.0	71.0	85.3	11	251
W2(a)	wet	3.9	121.8	121.8	148.1	17	400
			40.6	27.6	106.5	6	91
W3(a)	wet	3.5	131.8	131.8	150.2	19	473
			50.7	50.7	87.3	7	182
2W0-1(c)	wet	3.4	116.7	124.8	124.8	14	324
			50.0	108.1	108.1	6	281
2W0-2(c)	wet	3.4	126.8	126.8	126.8	15	325
			37.5	49.2	52.8	4	124
2W4-1(b)	wet	3.7	78.6	165.4	188.7	8	357
			--	--	--	--	--
2W4-2(b)	wet	3.4	107.5	117.0	117.0	17	114
			112.5	100.0	115.5	13	246
2W9-1(b)	wet	3.2	111.6	133.9	148.1	13	340
			75.0	70.0	114.1	9	178
2W9-2(b)	wet	3.4	111.6	106.5	111.6	13	261
			81.0	76.1	137.1	9	187

1 in = 25.4 m
1 kip 1000 lbs = 4.45 kN
1 psi 6.9 kN/m^2

(a) = 1 brick wythe, panel 3 ft. x 3 ft. with wwf
(b) = 2 brick wythes, panels 4 ft. x 4 ft. with wwf
(c) = 2 brick wythes, panels 4 ft. x 4 ft. with no reinforcement

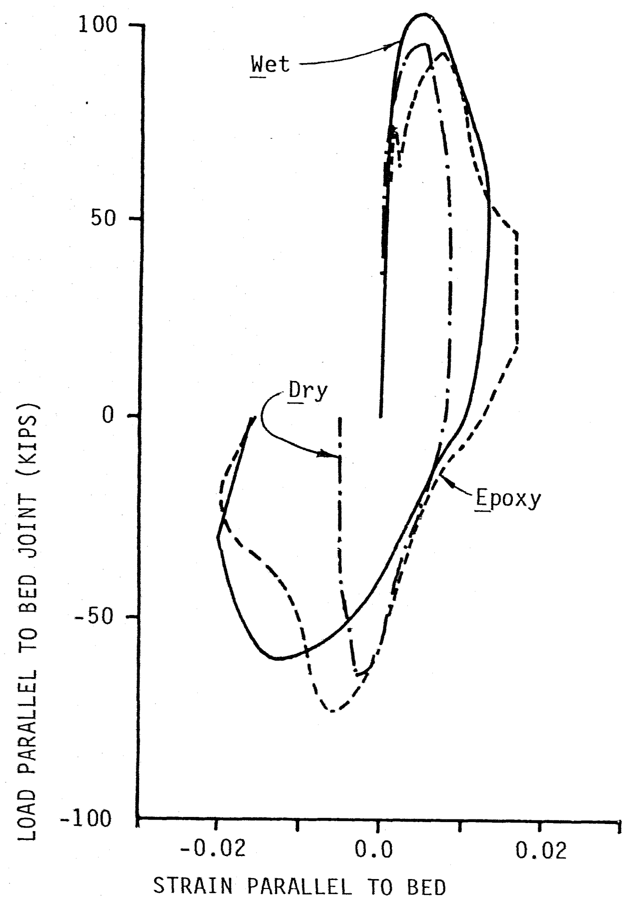

Figure 4. Average Load--Strain parallel to bed joint for D, E, W panels

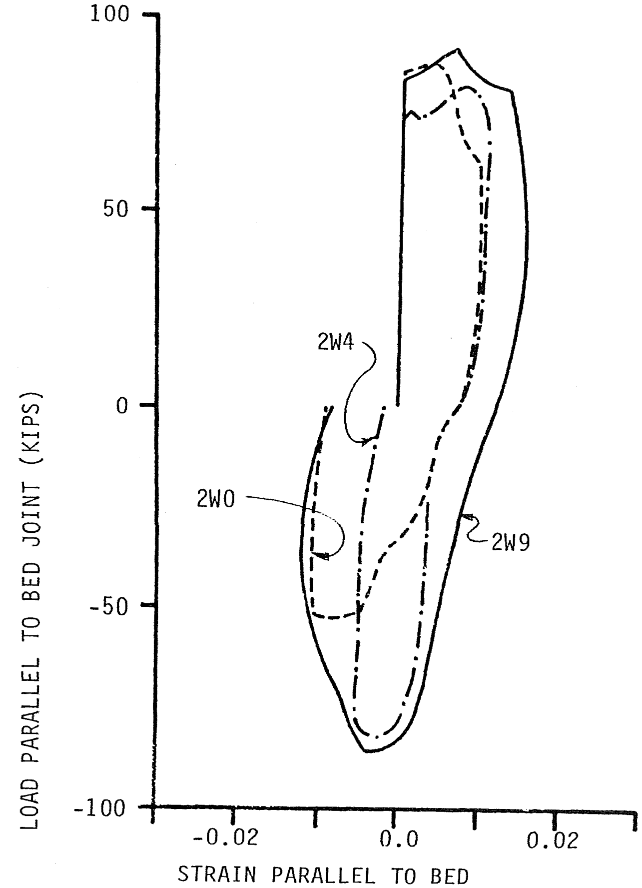

Figure 5. Average Load--Strain parallel to bed joint for 2W0, 2W4 and 2W9 panels