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Experimental results on the use of mud-based grouts to repair seismic cracks on adobe walls

Julio Vargas & Marcial Blondet
Pontificia Universidad Católica del Peru

Claudia Cancino
Getty Conservation Institute

Francisco Ginocchio, Carlos Iwaki & Kathya Morales
Pontificia Universidad Católica del Peru

ABSTRACT: This paper presents the main results obtained during an ongoing experimental test program performed to explore the possibility of repairing structural cracks on adobe walls through the injection of mud-based grouts. The structural objective was to attempt to recover the original strength of severely cracked adobe masonry elements by repairing them with mud-based grout injections. Masonry strength was first estimated with indirect tension tests of adobe sandwiches and later measured with diagonal compression tests of adobe masonry small walls. It was decided to study the use of grouts prepared with sieved soil alone or stabilized with lime, cement, and gypsum. The test results showed that grout injections based on the original soil used to build the walls are effective in restoring completely the original strength of adobe walls which had endured significant seismic damage. It seems, therefore, that a new criterion for the conservation of earthen buildings in seismic areas could be formulated, using compatible materials for the restitution of the original seismic strength of the earthen structural elements.

Keywords: Adobe, conservation, repair, cracking, grouts.

1 BACKGROUND

In seismic areas, it is crucial to be alert to the presence of cracks in the walls of adobe buildings, as they are the most important structural elements. Structural cracks may significantly reduce the stiffness and strength of the walls, and thus increase the risk of collapse during the occurrence of new earthquakes, with the consequent loss of lives and serious material damage to the cultural heritage.

Traditional methods of repairing earthen buildings are based on criteria of increased resistance. More recently, repair methods have been developed that are based on criteria of stability, by the use of tension-resistant reinforcement (Tolles et al. 2000, 2003). These criteria are complementary, and must take into account the recommendations of the *International Conservation Charts* that are universally accepted.

This project aims to study the feasibility of repairing cracked earthen walls through injections of liquid grouts made of only mud and of mud stabilized with cement, lime or gypsum (Vargas 1979, Mattone et al. 2005).

2 TESTING PROGRAM AND EXPERIMENTAL METHODS

One hundred fifty indirect tension tests were performed, using adobe "sandwiches" made by joining two adobe blocks with a layer of mortar made of mud sifted to remove particles larger than 2 mm. Batches of three similar sandwiches were tested. Each batch was made from mortars of 10 mixes of mud with and without additives, and of 5 nominal thicknesses (2 to 10 mm). Mortars were studied of only soil; soil stabilized with cement in 5%, 7% and 10% ratios, soil stabilized with lime (5%, 7% and 10%) and soil stabilized with gypsum (5%, 10% and 20%). Finally, a series of diagonal compression tests were conducted on small adobe masonry wall specimens. Fifteen specimens were cracked under diagonal compression, repaired

Figure 1. Device developed to perform indirect tension test on adobe sandwiches.

by injecting grouts of only soil and soil stabilized with cement, lime or gypsum, and tested again in order to measure the effectiveness of the repair procedure.

2.1 *Initial considerations*

Adobe masonry consists of a series of sun-dried blocks joined by mud mortar. The strength of the masonry results in large part, therefore, from the adhesion and resistance of the mortar. There are many alternatives for improving the quality of the mortars in order to attain stronger masonry (Vargas 1979). The joints are generally the critical areas of the adobe wall, as cracks in the mortar due to drying shrinkage reduce the adherence of the mud mortar to the adobe blocks. It is possible that a similar phenomenon occurs with grouts injected into the cracks in the walls. The quality of construction also has a great influence on the strength of adobe walls.

It seems reasonable to assume that the strength of adobe masonry buildings with walls that have been repaired with injections of grouts of stabilized soil is due to a combination of the strength of the grout and of the original mortar. While it is possible to make the strength and adhesion of the grout surpass those of the original mortar, this does not necessarily mean that the repaired wall will achieve a greater strength than the original, because when faced with a significant loading, the wall would simply fail in a different area than that which had been repaired.

2.2 *Indirect tension test*

The indirect tension test consists of vertical compression of a "sandwich" of two adobe blocks joined by mortar, forming a vertical and centered joint (Fig. 1).

The force applied causes fairly uniform tension stresses at the mortar-block interface (Fig. 2). The tensile strength of a sandwich is expressed by $\sigma_t = \alpha (P/A)$, where P is the breaking force, A is the area of the mortar interface ($A = lh$, where h is the height and l, the length of the sandwich) and α is a dimensionless factor to estimate the maximum tension stress at the interface.

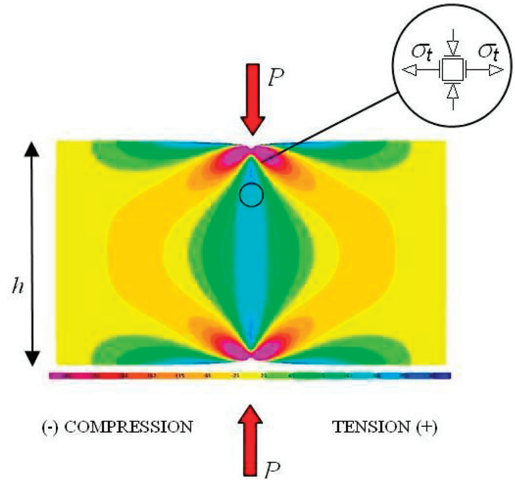

Figure 2. Distribution of normal horizontal stresses on adobe sandwich subjects to indirect tension test. The area directly below the load is in tension. The sandwich opens at the mortar-block interface.

A large number of mortar mixes were tested using this simple and inexpensive test. Although test results have a large dispersion, there is a significant correlation to more sophisticated tests, such as the diagonal compression test (Vargas et al. 1986). Both the blocks and the mortars were prepared with soil from the PUCP campus, which has a high percentage of materials with low plasticity. For the study of mortars, the moisture content and the maximum size of particles were varied.

2.3 *Diagonal compression test*

In this test, a square sample of masonry is subjected to a compressive force in two opposing corners (Fig. 3). The behavior of the specimens is representative of the seismic behavior of adobe masonry (Vargas et al. 1986), but the test is elaborate and costly, so it has been used only to test the most efficient grouts. The distribution of force is similar to that which occurs in the indirect tension samples and so, the type of failure expected is a crack between the points of application of the force, generated by the dominant tension stresses.

After testing, the failed specimens were transported to a repair area, and were placed in their "natural" position (horizontal rows) to have gravity acting as it does in real walls. After being repaired through grout injection, and drying for 3 to 4 weeks, depending on the weather (Fig. 4), the samples were moved to the laboratory to be tested again under diagonal compression.

The failure load of the repaired samples was compared with that of the original samples to assess the

Figure 3. Diagonal compression test of adobe masonry.

Figure 4. Repairing wall specimens through injection of mud-based grout.

degree of strength restoration achieved by the repair. It is important to note that while in the indirect tension tests, the mortars were of different mixes, in this case, mortars were always made of mud and the grouts were made of different mixes.

2.4 *Injection process*

The process of repairing by injecting mud grouts was conducted in the following steps:

1. Seal the crack faces with gypsum. Also place, passing through the gypsum seal, 3-mm diameter

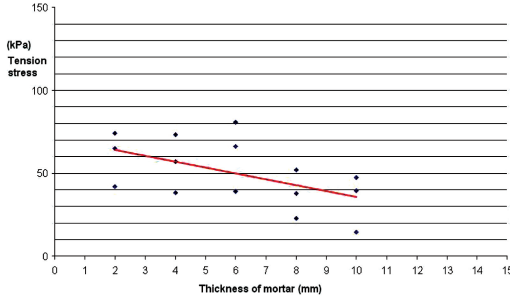

Figure 5. Results of indirect tension tests. Tension stress in the mortar-adobe interface in sandwiches with earthen mortar with 25% moisture. The thinner mortars tend to improve tension strength at the interface. The curve corresponds to a linear adjustment using the least squares method.

plastic tubes in order to form the holes through which the grout will be injected. Once the gypsum is hardened, the tubes are removed to leave the holes open.
2. Inject water into the holes. This procedure is to prevent the fine material on the inner surface of the cracks from insulating the injected grout. It also seeks to provide better lubrication for the injection of the grout and increases the moisture in the crack walls, decreases the rate of drying and reduces the formation of micro-cracks in the filling material.
3. Immediately inject the grout from the bottom up, through the holes. Grout is injected through a hole until the material has reached the level of the next higher hole and begins to escape.
4. Remove the gypsum seal and retouch the outer surface of the injected fissure to achieve an acceptable finishing.

The equipment used is a discarded cylindrical injector, which was originally sold in hardware stores to place putty for glass, or silicon. In the process of selecting injection equipment, more sophisticated pressure equipment, pressurized water pumps and other possibilities were ruled out.

3 EXPERIMENTAL RESULTS

3.1 *Mud mortars and grouts without stabilizers*

The results of indirect tension tests in sandwiches revealed that thinner mortar obtained greater tension strength, as shown in Fig. 5. The values obtained were similar than those reported for adobe masonry (Vargas et al. 1986). It was difficult to make sandwiches with mortar less than 2 mm thick, as it failed to adhere to the blocks.

To try to understand the influence of the thickness of the mortar on the strength of the adobe masonry,

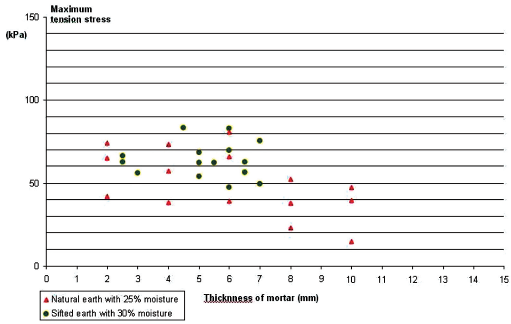

Figure 6. Maximum tension stress in the interface of sandwiches with natural soil mortars +25% moisture and sifted soil mortars +30% moisture. Sifted soil mortars are, on average, more resistant.

it was decided to make a series of sandwiches built with decreasing mortar thicknesses. After 48 hours, they were opened and the number and width of the cracks in the mortar were measured. It was found that although the number of cracks was similar in all specimens, in the thinner mortars the fissures were finer. It seems, then, that the greater strength in thinner mortars is due to the reduced thickness of the micro-cracks. Eight specimens made with 5 mm thick mortar were also built and tested in diagonal compression. These specimens were, on average, 150% stronger than traditional walls made with mortars 15 to 25 mm thick.

These results indicate that it is possible to build stronger adobe masonry by reducing the thickness of the mortar and, in the walls repaired by injection, it could be expected that the repair of thinner fissures would lead to greater strength recovery.

To produce finer and more diluted mortars and grouts, the earth was sifted with a #10 (2 mm) sieve, leaving large sand particles in the soil, which helped to reduce microcracking due to drying shrinkage (Vargas et al. 1986). Thirty to 40% moisture was used in the mixtures. Figure 6 shows the indirect tension test results. Mortars made of sifted soil with high moisture levels can be placed in thin layers (2 to 5 mm), to fabricate stronger sandwiches than those made with natural soil mortars.

Five 150 mm thick adobe masonry wall specimens with 15 mm-thick mortars were made and tested under diagonal compression. The specimens were subsequently repaired with natural soil grouts sifted through a #10 mesh and with nearly 40% moisture, and retested. Table 1 shows the results. In most of the wall sections, the original strength increased. In the two cases that failed to recover the strength, errors in repairing had been previously observed. These results indicate that it is possible to successfully repair cracks from 3 to 5 mm thick in adobe walls by carefully injecting grouts of mud without stabilizers.

Table 1. Strength recovery in repaired wall sections with grouts of sifted soil.

Wall section	Force of fracture (kN) Initial	Force of fracture (kN) Repaired	Recovery of resistance
MDNR-1	7.40	8.43	114%
MDNR-2	6.20	4.44	72%
MDNR-3	8.93	9.63	108%
MDNR-4	8.44	3.65	43%
MDNR-5	6.83	9.17	134%

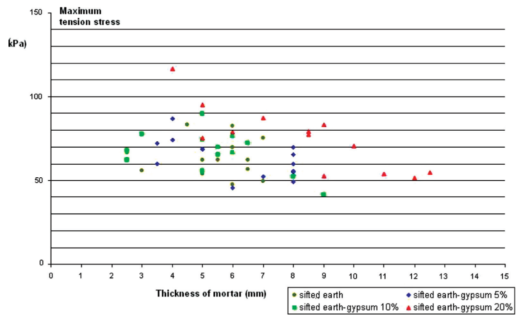

Figure 7. Maximum tension stress in the mortar-adobe interface in indirect tension tests of sandwiches with mortars of sifted soil stabilized with gypsum. Only the mortars with 20% gypsum achieve greater strength than those of sifted soil.

In general, diagonal compression testing produces one or two large cracks, without visible cracking nearby. Only visible cracks were repaired. In cases of effective repair, the cracking of the repaired wall specimens followed a path distinct from the original. When the repair was not well done, cracking of the repaired specimen occurred along the path of the original, poorly repaired crack.

3.2 *Mortars and grouts of stabilized mud*

To study the effect of the addition of cement, lime or gypsum to mortars and grouts, several series of indirect tension tests were conducted, using sandwiches with mortar prepared with percentages of stabilizers ranging from 5% to 20% of the total weight of the soil. The strength of these sandwiches was compared with that obtained in sandwiches with mortar of natural sifted mud and about 35% moisture.

The results with the gypsum stabilizer in 5%, 10% and 20% percentages were generally better than those obtained with lime and cement. However, only the gypsum in percentages of around 20% improved the strength obtained with mortars of natural sifted soil, as shown in Fig. 7. This result could be attributed to the fact that the gypsum being in contact with moisture in the mixture increases the volume,

Table 2. Strength restoration in wall specimens repaired with grouts of sifted soil stabilized with gypsum in 10%, 20% and 30% proportions.

Gypsum content	Wall specimen	Force of fracture (kN) Initial	Repaired	% Strength recovery
10%	MDNR-8	7.62	6.59	86%
	MDNR-9	9.11	10.25	113%
	MDNR-11	7.40	3.59	49 %
	MDNR-12	7.37	5.96	81%
20 %	MDNR-7	9.46	12.79	135%
	MDNR-13	5.55	11.21	202%
	MDNR-15	10.44	6.37	61%
30 %	MDNR-10	5.43	9.27	171%
	MDNR-14	8.32	8.63	104%
	MDNR-20	13.22	15.14	115%

which reduces the drying shrinkage of the earthen mortar, and therefore reduces the micro-cracking and increases the strength. The increased volume of the mortars stabilized with gypsum has been confirmed by measuring the volumetric shrinkage of 20% gypsum pastes (Mattone et al. 2005).

The strength of the sandwiches prepared with stabilized soil with lime or cement, in 5%, 7% and 10% percentages, was generally lower than that obtained with sifted soil. Therefore, only adobe wall specimens repaired with injection of grouts of sifted soil and sifted soil stabilized with gypsum were subject to diagonal compression tests.

Soil from the PUCP was used in manufacturing and repairing the diagonal compression specimens. The cracked specimens were repaired with grouts of sifted soil with 10%, 20% and 30% gypsum. The percentage of moisture used, from 35% to 40%, is the minimum needed to practice injection of the grout. Injections of grouts stabilized with gypsum were more difficult to do than those of only soil, because the gypsum makes the grouts harden faster. Table 2 shows the degree of strength restoration obtained.

The results show that in order to increase the strength of the adobe masonry walls repaired with soil, it is necessary to add gypsum in percentages between 20% and 30%. However, it is possible that the relative difficulty of the process of repair using grouts with gypsum could affect the quality of the repair.

4 CONCLUSIONS AND RECOMMENDATIONS

The proposal to repair structural cracks in historic adobe buildings appears to be a viable alternative, based on criteria of resistance, to return the building to its original, uncracked condition.

Repair by injection of grouts made of soil without stabilizers was effective for recovering the strength of the cracked adobe walls. Good quality of the injection process is crucial to achieving effective repair.

Stabilizing mud mortars by adding cement or lime did not produce good results. Gypsum was the best of the stabilizers studied. However, its use is questionable, since gypsum increases the difficulty of the repair.

A thinner mortar increased adobe masonry strength. This implies that by grouting thinner cracks, a more effective repair may be obtained.

Further research is necessary on repairing thinner structural cracks and thicker walls, in order to cover all the cases presented in historical adobe monuments. New types of grouts and more efficient injection techniques must continue to be explored. Emphasis should be placed on the use of natural and processed additives through the study of their mechanical and physical-chemical properties.

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