Seismic Retrofit of URM Walls with Fiber Composites

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One of the most serious problems facing the earthquake engineering community today is the very large number of older masonry buildings in seismic regions that were built before any provisions for earthquake loading were required. These structures are usually constructed from clay or concrete masonry units and in older cases, stone. The units are tied together by a cement or lime mortar; in many cases, little if any reinforcing steel is used.

While there are several types of masonry structural elements within a building, the most commonly used that are subject to earthquake damage, are walls. Walls are planar elements with or without openings that are designed primarily to carry the vertical loads within the structure. In a seismic event, however, they must also carry in-plane shear or out-of-plane flexural loads resulting from the earthquake. The damage caused by the lack of or insufficient reinforcement in these elements has been well documented through recent earthquakes [1–4].

The high risk of earthquake damage to such older masonry walls, particularly when unreinforced, and the potential for a great loss of life and property has made masonry structures the subject of a wide range of research studies [5–7]. One subject that is of great interest to the engineering community is that of developing methods whereby the lateral load-carrying capacity of these structures can be enhanced to satisfy modern seismic design codes. This is evident from recent research initiatives such as TCCMAR between U.S. and Japanese researchers [8] and the renewed interest taken by some European countries [9].

The methods for strengthening of masonry structures can be divided into two general categories. In one case, significant structural elements are added to the existing structure, resulting in a substantial change of the load path in the structure. In the other case, the wall surfaces are covered with various coatings to increase strength and ductility. The method discussed in this paper relates to the latter approach. Some related studies are discussed below.

Kahn tested nine single wythe 3 ft × 3 ft (0.91 × 0.91 m) and six 4 ft × 4 ft (1.22 × 1.22 m) double wythe brick panels strengthened with a 3.5 in. (89 mm) layer of shotcrete [10]. The effects of various surface treatments and the use of dowels on the bond between the shotcrete and the wall were studied. He concluded that full composite action could be developed if a saturated brick, wetted surface is used and that there is no need for the use of dowels or epoxy treatment of the wall surface prior to the application of shotcrete.

Researchers in New Zealand tested six masonry wall panels strengthened with a variety of techniques such as longitudinal prestressing, shotcrete on one surface, glass-reinforced cement on both surfaces, a combination of dowels, and steel-fiber reinforced coating on two surfaces, and the addition of a ferrocement wall to one side of the wall [11]. Ferrocement, as it is usually used, is an orthotropic composite material having a high-strength cement mortar mix and reinforced with layers of fine steel wires in the form of a mesh. The mortar strength results in a high composite compressive strength of 5 to 8 ksi (34 to 55 MPa) which is dependent on the volumetric reinforcement ratio (0.5% to 5%), the mesh type, and its orientation. The specimens were subjected to in-plane reversed cyclic loading. The solutions involving spraying of concrete, and in particular the use of steel-fiber reinforced coating, were determined to be the most viable alternative. This strengthening technique resulted in remarkably stable hysteresis loops.

Studies on strengthening of masonry walls with ferrocement overlays have been also conducted in the U.S. [12]. Seven square panels 25 × 25 in. (635 × 635 mm) were strengthened with a 0.5-in. (13 mm) thick coating of ferrocement with varying amounts of galvanized welded wire fabric. The fabrics consisted of square grids ranging from 1/8 to 2 in. (3 to 51 mm). The diagonal split or "Blume" test was used to determine the in-plane shear strength of the specimens. The load-carrying capacity of all strengthened specimens was nearly doubled and the largest ductility was obtained in specimens of medium-size mesh. The tests demonstrated that two modes of failure are possible. One is a ductile diagonal tension split of the entire composite section which is accompanied by large inelastic deformations. The other is a more brittle failure at the interface of the wall and the coating.

Other researchers have also examined the effects of various surface treatments on increasing the in-plane shear capacity of walls [13–15]. In a study conducted at the University of California-Berkeley, masonry walls coated with either reinforced plaster or fiberglass reinforced mortar were tested with monotonic cyclic loads or by simulated earthquakes [16]. The strength of these walls were nearly doubled and the coating increased the ductility of the system.

Most of the retrofit techniques developed to date are rather expensive to implement. Consequently, unless mandated by law, the costs associated with such strengthening techniques have prevented most building owners from voluntarily adopting these modifications. As discussed later, the method described here is a cost-effective technique for seismic retrofitting of masonry structures. The technique, which uses fiber composite materials, is an extension of earlier work of the authors on strengthening reinforced con-

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crete [17–19] and masonry beams [20]. Fiber composite materials have been used successfully for strengthening of structures. In Switzerland, laminated sheets of graphite have been externally bonded to reinforced concrete beams to enhance their flexural strength [21]. Japanese researchers have also reported on seismic retrofitting of circular concrete sections such as chimneys and columns by wrapping continuous spirals of carbon fibers around them. The strength and ductility of the retrofitted structures was significantly improved [22].

COMPOSITE MATERIALS

Composite materials are made up of fibers (e.g., glass, graphite, Kevlar) bonded together with a resin matrix. For the composite materials discussed here, the fibers are long and continuous. The fibers are the primary load-carrying elements and provide the composites with their unique structural properties. The resin serves as the bonding agent to protect the fibers and to distribute the load among them. Depending on the type of application, the fibers can be oriented in a multitude of directions to enhance the mechanical properties of the composite in the desired direction. Fig. 1 shows a typical fabric in which equal amounts of fiber are placed in the 0 and 90 degree directions.

The use of composites for a variety of industrial applications has been rapidly increasing in recent years. The main reasons for using composites are their superior strength-to-weight ratio, stiffness-to-weight ratio, and durability in corrosive environments as compared with conventional materials. In addition to the superior strength properties, many composites have shown much better fatigue performance than structural metals. Composites have been used extensively in aircraft and aerospace industries. The first recorded application of glass-fiber-composites in the aircraft industry dates as far back as 1944 [23]. Since then, a variety of composites have been used in other industries such as ship building, chemical processing, medical, and automotive.

Moisture and temperature are known to have adverse effects on composites and adhesives. The change in structural behavior of composites primarily results from the effect of moisture and temperature on the resin system that bonds the fibers. Considerable effort is now being devoted to the development of resin systems and adhesives that are less prone to moisture adsorption than the earlier generations of epoxies. The most promising of these to date seems to be PEEK (Polyether-Ether-Ketone) and Phenolic-Resin systems which are highly moisture insensitive. Even though there are still some uncertainties in the behavior of composite materials, as far as is known, no major problem has so far arisen due to either environmental effects or fatigue in composite components of aircraft in service [23]. Some such components have been in service for more than 30 years.

Fiber composite materials generally have a linear, elastic stress-strain relationship. Fibers of E-glass, for example, have a tensile strength of over 300 ksi (2068 MPa) and a modulus of elasticity of about 10,000 ksi (69 GPa). In most cases, the fibers account for 60% to 70% of the volume of the composite, with resins making up the balance. Therefore, for glass-fiber-reinforced composites, a tensile strength in the range of 80 to 150 ksi (550 to 1035 MPa) and a modulus of elasticity of about 6000 to 7000 ksi (41 to 48 GPa) is common.

There are, of course, other fibers such as carbon that in composite form are both stronger and stiffer than glass. However, these fibers are rather expensive and may have limited application in the construction industry where large volumes of inexpensive material are needed. Fig. 2 shows typical stress versus strain diagram for glass and carbon fiber-reinforced composites (GFRP and CFRP, respectively) and steel.

STRENGTHENING WITH FIBER COMPOSITES

The primary shortcoming of masonry walls is their inability to resist tensile stresses. While this problem can be easily resolved in new construction by incorporation of reinforcing steel, the issue has been challenging in existing structures where the axial loads may be low, and little or no reinforcement is present.

Recognizing the high tensile capacity of fiber composites, a thin layer of these materials (in fabric form) can be epoxied to the exterior surface of the wall (Fig. 3). The fabric could contain fibers positioned in both horizontal and vertical directions to increase both the flexural and shear strength of the wall. As shown in Fig. 4, for a wall subjected to bending, the internal tensile stresses in the composite

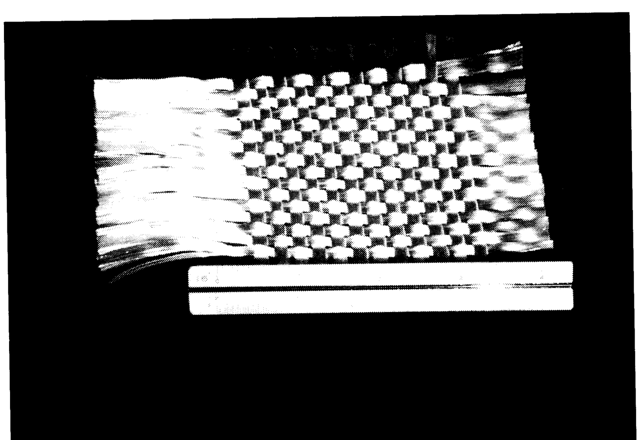

Fig. 1—Typical fabric with equal amounts of fiber in the 0/90 degree directions

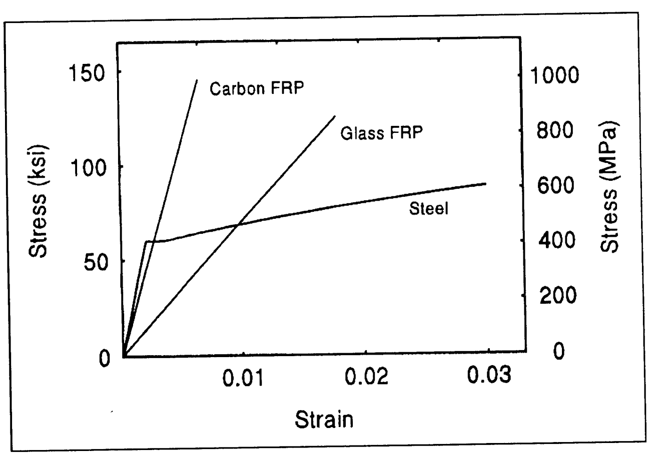

Fig. 2—Stress versus strain behavior of steel and composites

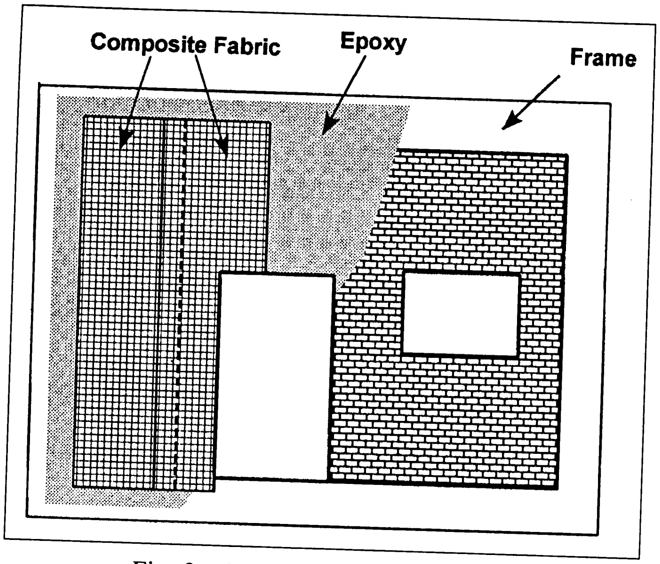

Fig. 3—Schematic of the proposed strengthening system

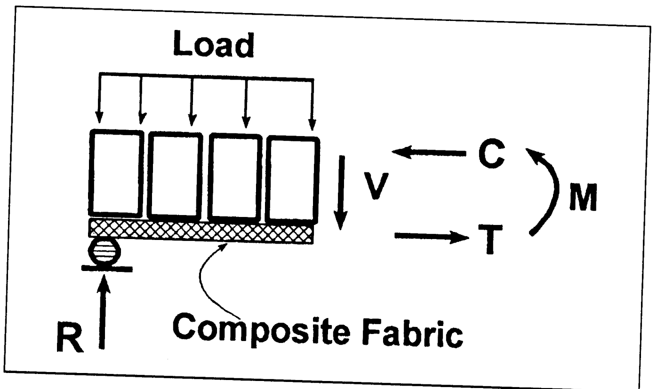

Fig. 4—Mechanism for resisting flexure

fabric will be resisted with internal compressive stresses in the masonry, resulting in a resisting moment. For an element subjected to diagonal tension or shear, the forces along the inclined crack are resisted by the sum of the forces developed in the individual horizontal and vertical fibers of the fabric (Fig. 5). In this case, the composite fabric acts the same way as a grid of steel reinforcing bars embedded within the wall, with the rebars placed in the horizontal and

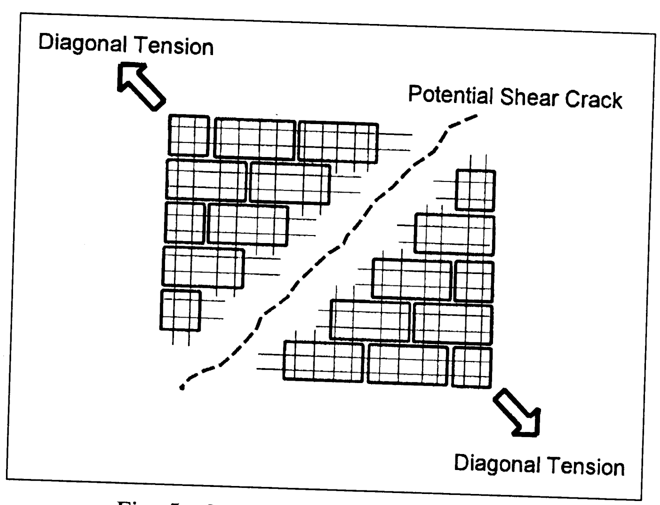

Fig. 5—Mechanism for resisting shear

vertical directions. The degree of strengthening can be designed according to the strength of the composite fabric being used and of the substrate material. The principles illustrated in Figs. 4 and 5 are applicable to all types of substrates, such as bricks, concrete block, and hollow clay tiles.

The steps required to strengthen an infill frame can be summarized as follows:

a) The wall surface is cleaned of any external coatings.
b) If necessary, the mortar joints are filled to obtain a surface that is flush with the masonry units.
c) A thin layer of epoxy is applied to the wall surface and to the adjacent beams and columns (Fig. 3).
d) The fiber composite fabric is placed over the epoxied areas of the wall and the adjacent beams and columns.
e) With the help of a roller, the fabric is pressed onto the epoxy and if necessary, an additional coating of epoxy is applied to the outside of the fabric so that the fabric is fully saturated with epoxy.
f) The epoxy dries in about an hour and will fully cure in 24 hours, leaving the wall with a textured finish similar to that of cloth wall coverings.
g) If desired, the retrofitted wall can be covered with stucco, plaster, wallpaper, paint, etc. These coatings could provide protection against ultraviolet rays and fire.

Because this retrofitting system covers the entire wall surface, its application to the exterior walls of some buildings may be objectionable from an architectural point of view. However, it is possible to remove the facade of the wall first and replace it later after the wall has been strengthened. Alternatively, the textured top coating of the wall can serve as the final finish for the wall.

Advantages of the Technique

Strengthening of masonry structures with fiber composites has several advantages over the use of conventional approaches. Some of the salient advantages are listed below:

a) The presence of the fabric confines the wall and prevents the individual masonry units from separating from the wall and causing collapse of the wall or loss of life and property.
b) Attaching the edges of the fabric to the adjacent beams and columns will in many cases prevent the collapse of the wall as a whole unit. At present, infill walls are primarily supported at their bases only by their self weight; by attaching all four edges of the wall to the adjacent beams and columns of the frame, the wall behaves as a two-way slab. This is of great significance in many applications such as hollow clay tile infill frames, where the potential collapse of the brittle clay tiles during an earthquake poses a major hazard to the occupants.
c) Unreinforced masonry walls have limited flexural capacity. The proposed retrofit enhances out-of-plane flexural capacity of the wall.
d) The horizontal and vertical fibers in the fabric greatly increase the in-plane shear capacity of the wall.
e) The fiber composite fabrics add very little weight to the structure and therefore does not increase the inertial forces caused by an earthquake.
f) The small weight added to the wall does not require any strengthening of the foundation.

g) The method increases the wall thickness by a negligible amount (about 1/8 in. [3 mm]) and little valuable floor space is lost as a result of the strengthening.
h) The fiber composite fabrics can be easily cut in the field (with an ordinary pair of scissors) to allow for openings in the wall. This greatly simplifies the construction and saves labor costs.
i) The need for drilling holes in the walls to accommodate anchor bolts is reduced or eliminated; this is particularly important in older buildings where such drilling may further weaken the wall.
j) The light weight of the fabrics and the simplified method reduces construction time; this is particularly of interest in buildings that are occupied during the retrofit process or when the walls are not easily accessible.
k) In most cases, the method costs less than conventional retrofitting.
l) In spite of their high tensile strength, the fabrics can be easily drilled through or penetrated with nails and bolts; thus, the retrofitted walls easily accommodate the attachment of non-structural or decorative items.

The main disadvantage of the technique is that it covers the wall surface and therefore it may not be a suitable solution when the building's owner wants to maintain the brick appearance of the wall. Furthermore, if the bricks are highly deteriorated, they may not provide the strong surface that is required for bonding of the fabrics.

EXPERIMENTAL STUDIES

The enhancements in flexural and shear strength of URM that are gained with fiber composites have been examined through laboratory and field tests discussed below.

Flexural Strengthening of URM Walls

The out-of-plane flexural behavior of unreinforced masonry (URM) walls was studied by testing small URM beams. The beams consisted of 19 solid clay bricks, each with a dimension of 2.5 × 4 × 8.5 in. (63 × 102 × 216 mm), stacked in a single wythe (stack bond). This resulted in beams that were 8.5 in. (216 mm) wide, 4 in. (102 mm) high and 57 in. (1.45 m) long. The beams were loaded statically to failure with two concentrated loads over a clear span of 47 in. (1.19 m) (Fig. 6).

Each beam was identified with a combination of 4 characters. The first numeral, 1 or 2, refers to the type of epoxy. Two epoxies were investigated. The first was a two-component epoxy that performed exceptionally well in previous studies for strengthening of reinforced concrete beams [17, 19]. Among the features of this epoxy are its high energy absorption, resistance to high humidity, salt spray, cold and hot environments, and economy. The epoxy has a consistency similar to cement paste with a pot life of approximately 0.5 hour. It is fully cured at room temperature in four hours. A dual-component dispensing tool was used to achieve a uniform mixture of the epoxy as it was being applied to the wall and fabric. The second adhesive being studied was also a two-component epoxy that cures at room temperature. This epoxy had a lower viscosity than the first and can be easily spread over the wall surface with a trowel. According to the manufacturers, both epoxies had the following mechanical properties: tensile strength, 2,000–2,500 psi (13.8–17.2 MPa); modulus of elasticity, 75,000–125,000 psi (517–862 MPa); and an elongation at failure of more than 15 percent.

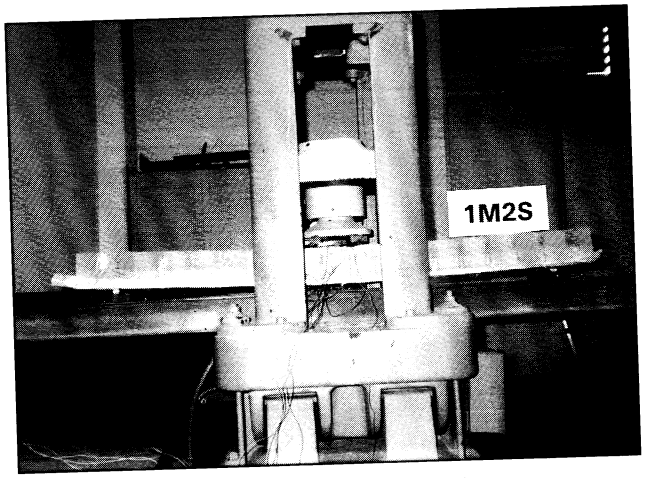

Fig. 6—Test setup for flexural tests

The letter M designates the type of mortar used in the study, which consisted of portland cement:lime:sand ratios of 1:0.25:3. To simulate the effect of a weaker mortar, which may be found in some older structures, one specimen was constructed with a mortar designated with M* with a ratio of 1:0.25:5.

The next numeral (1, 2, or 3) refers to the type of fabric used. Three different fabrics of various strength (thickness and weave pattern) were used to investigate the possibility of achieving various modes of failure, such as tension failure of fabric, or compression failure of brick.

The last letter (F or S) refers to the overall roughness of the wall where the fabric is attached. The intent was to investigate the effect of the surface finish on bonding of the composite fabrics. In both cases, the fabric was epoxied to the smooth surface of the brick. In one case, however, the mortar joints were flush with the outside surface of the wall (F); in the other case, a small amount of mortar extruded from the joints (S).

All specimens but one were constructed with new clay bricks. Because the age of bricks may influence their bonding characteristics to the epoxy, one specimen (1M2S-1) was cast with reclaimed old bricks. The results for six beams that were retrofitted and tested are presented here.

As mentioned earlier, two types of mortar were used in this study. The mortars were tested at 28 days as 4 × 8 in. (50 × 100 mm) cylinders. The compressive strength was calculated as 4650 and 4100 psi (32 and 28 MPa) for Type M and M* mortars, respectively. Prisms were constructed with the new brick and both mortars. The 28-day strength of the prisms was calculated as 1870 psi (12.9 MPa). The prisms failed by compression failure of the bricks; consequently, the slight change in the mortar strength did not have a significant effect on the overall strength of the specimens.

Three types of fabrics were used. The first one was a glass fabric with an acrylic polyvinyl finish which comprises approximately 6 to 10 percent of the product weight. The fabric weighed 5.6 oz/yd^2 (190 g/m^2) and had a visual 2 × 4 yarns/in. construction in the machine (warp) and cross-machine (fill) directions. According to the manufacturer, the tensile strength of the fabric as determined by ASTM-D579 with a 3-in. (75 mm) jaw separation at a crosshead speed of 12 in./min was 220 × 270 lbs/in. (38.5 × 47.3 N/mm) in the weak and strong directions, respectively. This fabric was epoxied to the specimens with the strong direction parallel to the length of the beam. The second and third fabrics contained unidirectional E-glass fibers. Five samples of each fabric were tested by the manufacturer in accordance with the out strip method of ASTM-D1682. The results indicated that the second fabric had 11.3 yarns/in. and a tensile strength of 1422 lb/in. (249 N/mm). The corresponding numbers for the third fabric were 10 yarns/in. and 855 lbs/in. (150 N/mm).

The beam specimens were subjected to four-point bending as shown in Fig. 6. Before discussing the results, the reader is reminded that when spanned horizontally in the testing frame, the unretrofitted test specimens would normally fail under their self weight of approximately 125 lbs (556 N). Therefore, prior to strengthening, the specimens had to be handled very carefully. The first fabric, used in Specimen 2M1S, was relatively weak. Nonetheless, the specimen carried a maximum load of 700 lbs (3114 N) and had a deflection of 0.27 in. (7 mm) at failure (Fig. 7). The ultimate load was defined as tension failure of the fabric. Based on this test, stronger fabrics were used in the remaining tests.

The influence of the strength of the fabric can be readily seen by comparing Specimens 1M2S and 1M3F, both retrofitted with the same epoxy (i.e. Type 1). The thicker fabric in 1M2S resulted in a failure load of 2850 lbs (12.67 kN) and a deflection of 0.63 in. (16 mm). Failure began with compression crushing of the bricks near the top of the beam, followed suddenly by diagonal cracking of the beam in the shear span (Fig. 8). Specimen 1M3F had less stiffness due to the thinner fabric used. This specimen reached a maximum load of 1320 lbs (5.87 kN) and a deflection of 0.65 in. (16.5 mm). At that point, the fabric failed in tension.

The performance of the second epoxy was superior to that of the first. This was evident from comparison of the results for Specimens 1M3F and 2M3F. Both specimens were retrofitted with the lighter E-glass fabric. The performance of Specimen 1M3F was discussed above. Specimen 2M3F had a higher stiffness and reached a load of 1950 lbs (8.67 kN) at a deflection of 0.98 in. (25 mm), or 1/48 times the span (Fig. 7). Thus, the failure of the specimen was ductile and accompanied by large deflection. Both specimens failed by tension failure of the glass fabric. However, the additional

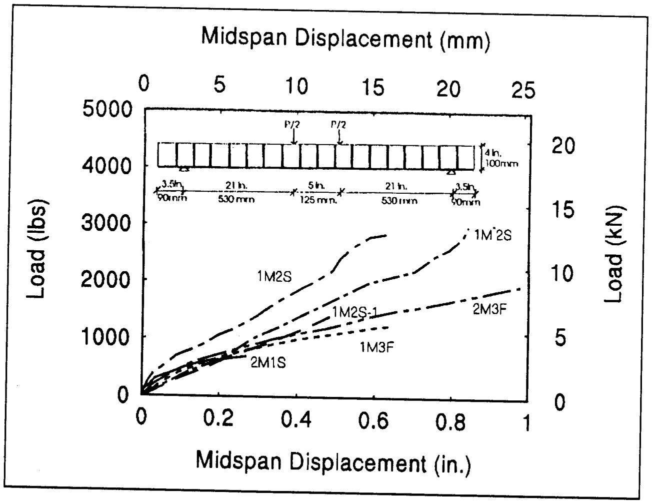

Fig. 7—Load versus deflection for retrofitted URM beams

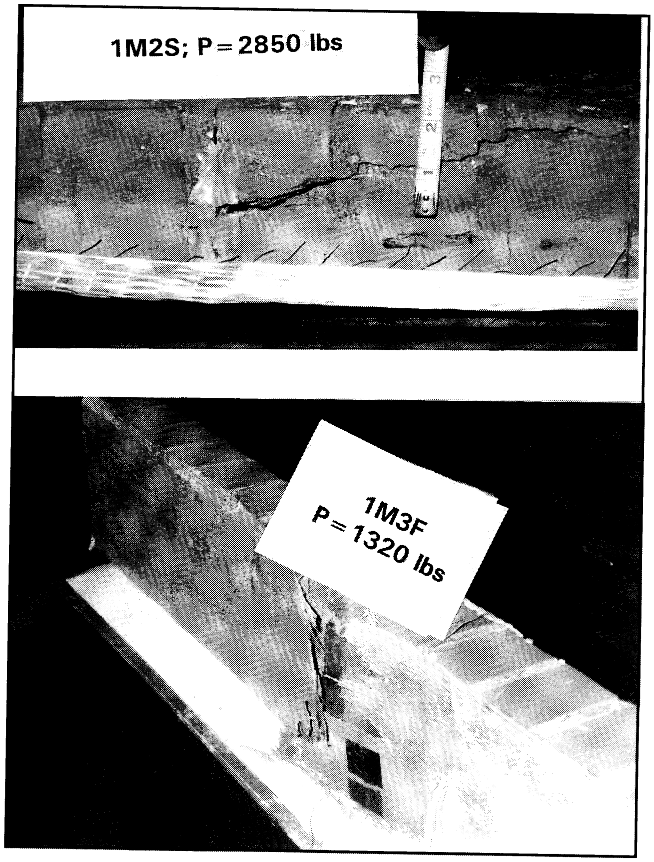

Fig. 8—Failure modes for flexural tests

load carried by Specimen 2M3F and its higher deflection at failure were attributed to the type of epoxy used in this specimen.

Comparison of Specimens 1M2S and 1M2S-1 can reveal information on the performance of the two types of brick used. Specimen 1M2S, constructed with new brick, had more stiffness and failed at a load of 2850 lbs (12.68 kN). Specimen 1M2S-1, which was constructed with old reclaimed brick, failed at a load of 1400 lbs (6.23 kN) and at a deflection of 0.48 in.(12 mm). Due to the large thickness of the fabric used, both of these specimens failed by compression failure of brick. Although no prism tests were performed for the reclaimed brick, it is believed that the lower strength of this brick resulted in the lower failure load for the specimen.

The effect of the mortar strength appeared to be negligible in these specimens. Specimen 1M2S with the stronger mortar failed at a load of 2850 lbs (12.68 kN) while its companion specimen with weaker mortar, 1M*2S, failed at a load of 3000 lbs (13.34 kN). This was nearly twenty four times the self weight of the beam. Both of these specimens were retrofitted with the thicker fabric and failed by compression failure of the masonry. In masonry prism tests, failure was initiated by compression failure of the brick rather than the mortar. Consequently, the slight difference in the strength of the mortar in these two specimens did not change the mode of failure and the maximum load carried by both specimens were comparable. Examination of the specimens during and after the tests indicated that none of them exhibited any visible sign of slip or bond failure at the epoxy-fabric interface.

The flexural strength of a structural element reinforced with composite materials can be calculated using theories of mechanics. These have been presented elsewhere [24]. Assuming that the epoxy is capable of transferring the stresses without any failure or slippage, the area of the composite can be selected to achieve the desired mode of failure. For members containing steel reinforcement, it is preferable to provide a large enough composite section so that the steel will yield first before the composite or masonry fail. For unreinforced masonry, it is also preferred to avoid rupture of the composite fabric. However, considering the flexibility of a URM wall retrofitted with composites, serviceability limits may control the design of most walls.

Shear Strengthening of URM Walls

In many older URM buildings, the existing mortar joints are weak and provide insufficient shear resistance to lateral loads. In such cases, the attachment of composite fabrics to the exterior face of the wall can supplement the strength of existing mortar to transfer shear among the masonry units. In addition to the flexural tests described above, direct shear tests have also been conducted on masonry specimens in the laboratory and in the field.

The laboratory specimens consist of three solid clay bricks which are covered with a composite fabric on both faces (Fig. 9). The fabric pieces are each 4.5 in. (114 mm) wide and 8 in. (203 mm) long. Several fabrics and epoxies have been tested. The results shown in Fig. 9 are for a fabric that weighs 10 oz/yd^2 (339 g/m^2) and has equal volume of fibers in the warp and fill directions. The applied load versus the deflection at the top of the middle brick has been plotted for two specimens. The solid line represents a specimen in which half of the fibers within the fabric were parallel and the other half were perpendicular to the axis of loading; the dashed line is the behavior of a specimen with the fibers crossing the shear plane at 45 and 135 degrees. In order to expedite the construction of the test specimens, no mortar joints were used. Instead, the bricks were separated from one another with lubricated spacers having a thickness of 3/8 in. (10 mm). Consequently, the resistance of the specimens was fully attributed to the composite fabric. In the test setup used, a steel clamping device was used to prevent out-of-plane movement (i.e. twisting) of the specimens.

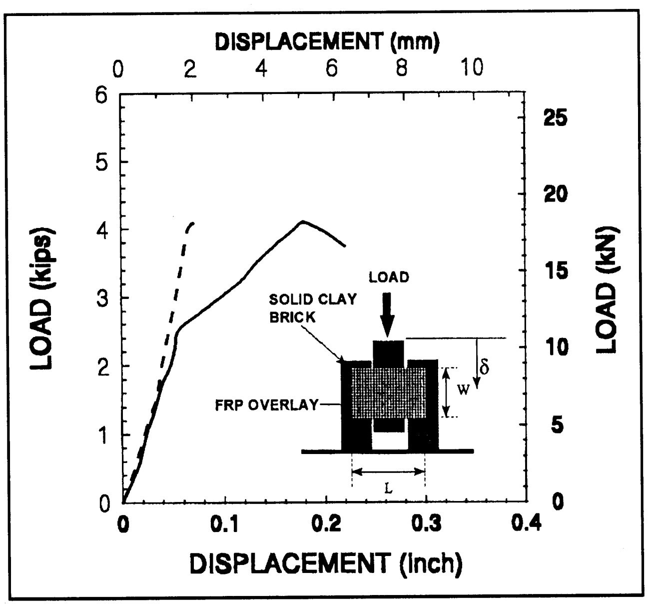

Fig. 9—Load versus deflection for shear tests

In both cases, the specimens resisted substantial forces prior to failure. Failure of the 0-90 specimen occurred as a result of a tearing of the composite fabric at the interface of the bricks. Failure was not brittle since the load resisted by the specimen increased up to a displacement of 0.2 in. (5 mm), with a reduction in stiffness after a displacement of 0.05 in. (1.3 mm), where the tearing of the fabric began. The 45/135 specimen had a higher stiffness. This is because with that orientation of the fabric, the fibers are subjected to direct tension, where the stiffness of the fibers is largest. Both specimens shown in Fig. 9 carried loads in excess of 4000 lbs (17.8 kN). A large number of such specimens incorporating fabrics with different strengths have been tested; the experimental results and the analysis of those specimens are presented elsewhere [25]).

The enhanced shear strength of such specimens cannot be properly presented in a manner similar to the standard in-place masonry shear tests. In the latter, the shear strength is a function of the area of the horizontal plane (i.e. bed joint) being tested. For the strengthening system discussed here, the forces are developed on the exterior (i.e. vertical) faces of the wall. For example, the failure load of 4000 lbs (17.8 kN) in Fig. 9, would not have changed if the bricks were hollow. Assuming that the contact area of the solid bricks used in the tests was 4 × 6 in. (102 × 152 mm), the shear capacity is 83 psi (0.57 MPa). If hollow bricks were used such that the area of the horizontal plane of contact was 15 in^2 (9680 mm^2), the same failure load would result in a shear capacity of 133 psi (0.92 MPa).

FIELD APPLICATIONS

Hollow clay tiles have been used as partition walls in many older buildings. However, because these units are no longer produced, construction of specimens for laboratory testing, which have to be made with reclaimed units, is not an easy task. In summer 1995, a unique opportunity came about where several hollow clay tile walls in the San Francisco City Hall Building which was undergoing seismic retrofitting were available for testing. The field tests modeled realistic conditions where the existing mortar joints and the weight of the wall do contribute to the shear capacity of the wall.

The field tests were performed by an independent laboratory which had earlier carried out the tests on the original unretrofitted walls to determine their shear capacity. The tiles were 12 × 12 × 4 in. deep (305 × 305 × 102 mm) and contained three cell units with typical wall thickness of about 0.5 in. (13 mm). The tan clay tiles had smooth internal surfaces. External surfaces had 1/8 in. wide × 1/8 in. deep (3 mm × 3 mm) triangular furrows, spaced at 3/8 in. (10 mm) on center, aligned parallel to the internal bores. Earlier, the laboratory had carried out in-place masonry shear tests of the existing unretrofitted walls per UBC Standard No. 24-7. The average shear strength based on five tests was 68 psi (0.47 MPa).

Portions of the same walls were tested after they were retrofitted by means of attaching 18 oz/yd^2 (610 g/m^2) fabrics to both faces of the wall (Fig. 10). The fabrics had equal volumes of fiber in the horizontal and vertical directions. The average shear strength of the retrofitted wall based on three tests was 237 psi (1.63 MPa), i.e. an increase of nearly

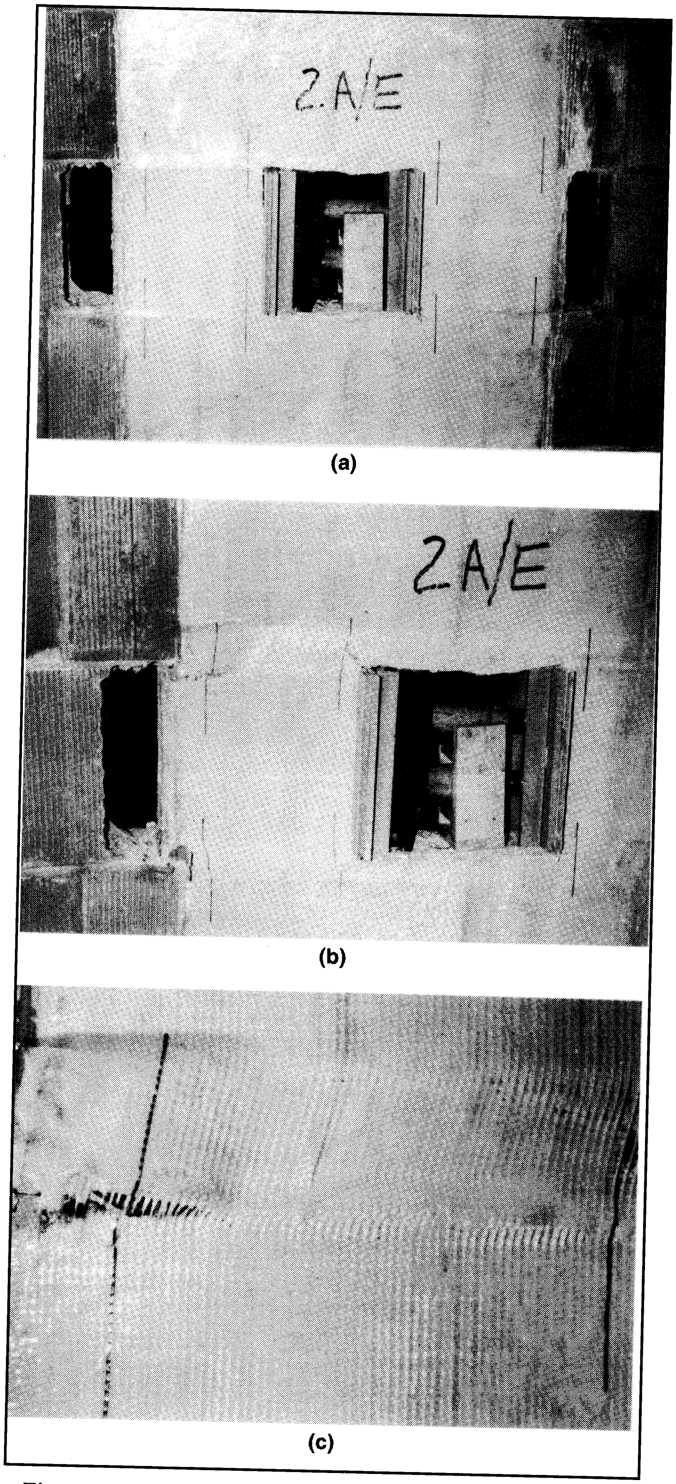

Fig. 10—In-situ shear tests of hollow clay tile walls in San Francisco City Hall Building: a) test setup; b) at maximum load; c) at conclusion of the test

350% above the unretrofitted case. The failure mode in all retrofitted tests was due to crushing of the hollow clay tiles. As shown in Fig. 10b, as the ultimate load was reached, the composite fabric was fully intact, showing no sign of damage. Only with additional extension of the jacks, did the broken tile move further and caused a distortion in the fabric. This is shown in Fig. 10c where the reference vertical lines drawn on the fabric indicate the displacement along the bed joint. Thus, the fabric was capable of developing the full strength of the hollow clay tiles. If the tiles were solid, the specimens would have resisted even higher loads.

One of the buildings damaged in the Northridge earthquake of January 17, 1994 was a one-story commercial building. The structure had been retrofitted a few years earlier by addition of a steel frame in the middle of the building and by tying the roof diaphragm to the walls with anchor bolts. Although that retrofit was effective in preventing collapse of the wall, tying the diaphragms to the walls results in larger forces being transferred to the walls. Consequently, in many retrofitted buildings where the connection of the floor diaphragms to the walls have been strengthened, overloading may result in severe damage to the walls themselves; in other words, the weakest link in the chain is now the wall rather than the wall-to-diaphragm connection. In this case, shown in Fig. 11, the south wall of the building which measures over 60 ft (18.3 m) long and 20 ft (6.1 m) high was severely cracked during the earthquake. The cracks in the wall had reduced both the flexural and shear capacity of the wall significantly. The 8 in. (203 mm) wide wall was constructed of unreinforced masonry block units. Other parts of the building had also suffered minor damage. The building was ordered closed by building officials until repairs were completed.

An examination of records revealed that when the building was being retrofitted a few years earlier, the results of the in-situ shear tests on the wall were misinterpreted. As a result, the shear capacity of the wall was over-estimated by a factor of two. If the correct shear capacity of the wall had been used, the weakness of the wall and the need for strengthening would have been apparent.

Standard repair for this wall would have required the addition of a new shotcrete wall on one side of the existing wall. This requires the placement of a mesh of horizontal and vertical steel reinforcing bars that are tied to dowels anchored in the existing wall; a layer of concrete, several inches thick, is then sprayed onto the wall. In this building, however, that option was not acceptable for the following reasons. The existing masonry wall rests on the property line, and therefore the addition of the shotcrete wall to the outside of the building, which would protrude into the neighbor's property, was not allowed. On the inside of the wall, existing hardware for the conveyor belt system of the dry-cleaning store are attached to the ceiling, very close to the wall. Addition of shotcrete would have required the removal of these railing systems, adding to the cost and construction delays for the project.

To overcome these limitations, a fiber composite strengthening technique was selected. The appropriate fabric strength and fiber orientation and epoxy system were selected. Most building codes, including the Uniform Building Code (UBC), allow alternative materials for construction, provided that supporting documents can be presented to the satisfaction of the building official. Because this was the first project to use this system, a number of questions were raised by the local building officials. Some of these questions concerned the structural behavior of the system. Those concerns were addressed by providing the officials with the laboratory test results. Other questions dealt with health, environmental, and fire safety issues of the composite system. After all these concerns were responded to in a satisfactory manner, the city issued the permit for construction.

The existing wall surfaces were sandblasted and cleaned of any loose particles. Several of the masonry units were

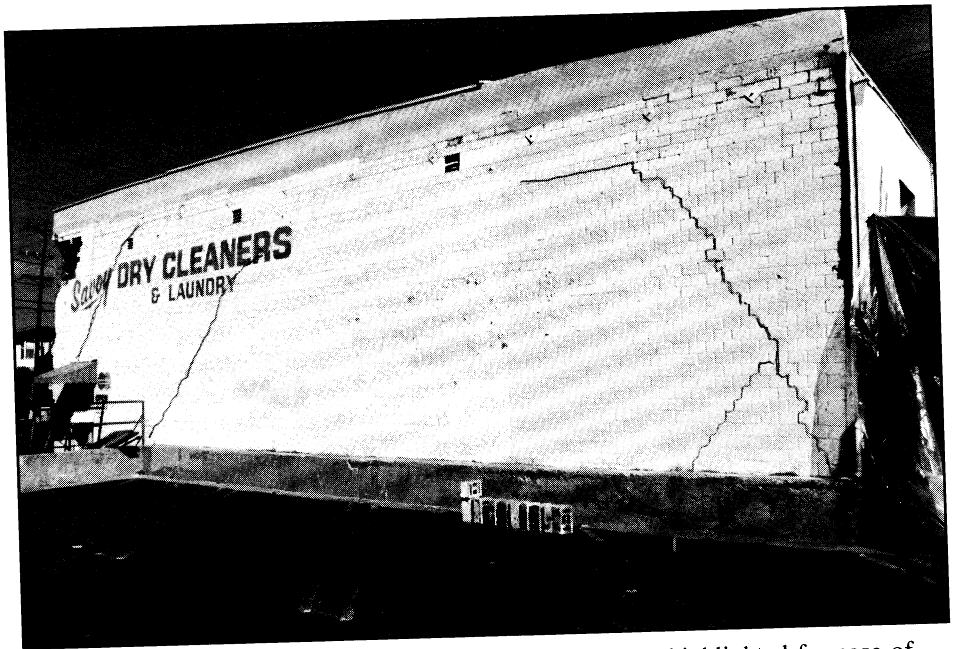

Fig. 11—Failure of URM wall-Major cracks have been highlighted for ease of identification *(Photo courtesy of External Reinforcement, Inc.)*

loose and were reset, and the shear cracks in the wall were filled with mortar. The two-part epoxy was mixed in the field and applied in thin layers to the wall. The 3-ft. (915-mm) wide fabrics were then placed on the wall in vertical strips and pressed against the uncured epoxy. In a similar fashion, the next strips of fabric were added with sufficient overlap with the adjacent strips to form a continuous fabric on the wall (Fig. 12). The nuts and washer plates associated with seismic anchors from the earlier retrofit were temporarily removed and were replaced after the composite fabric was installed. The bottom edge of the fabric was anchored to the existing footing with a steel anchor plate and bolts. On the exterior surface, the top edge of the fabric was anchored to the existing wall parapet. On the interior, the top of the fabric was wrapped around blockings which were fastened to the floor joists. Fig. 13 shows the interior wall surface at the completion of the project; the conveyor belt system and the bolts and straps which were used in the earlier retrofit to tie the roof to the wall can also be seen.

Once the fabrics were attached to the wall, a second coating of epoxy was applied to the exterior surface so that the fabric was totally impregnated with the epoxy. Finally, the exterior surface of the wall was covered with a special ultraviolet-protective coating; the coating color was selected to match the original color of the building. Fig. 14 shows the wall upon complete installation of *QuakeWrap*™ after the application of the ultraviolet-protecting paint.

The materials for a single layer of fabric, epoxy, and the top coating cost less than \$4/ft^2(\$43/m^2). Depending on the height of the wall and access constraints, each worker can complete an area of roughly 100 ft^2/day (9 m^2/day). Thus, compared to other alternatives, this retrofitting system is very cost-effective; estimates for shotcreting a wall in southern California, for example, range from \$20 to \$30/ft^2 (\$215 to \$325/m^2).

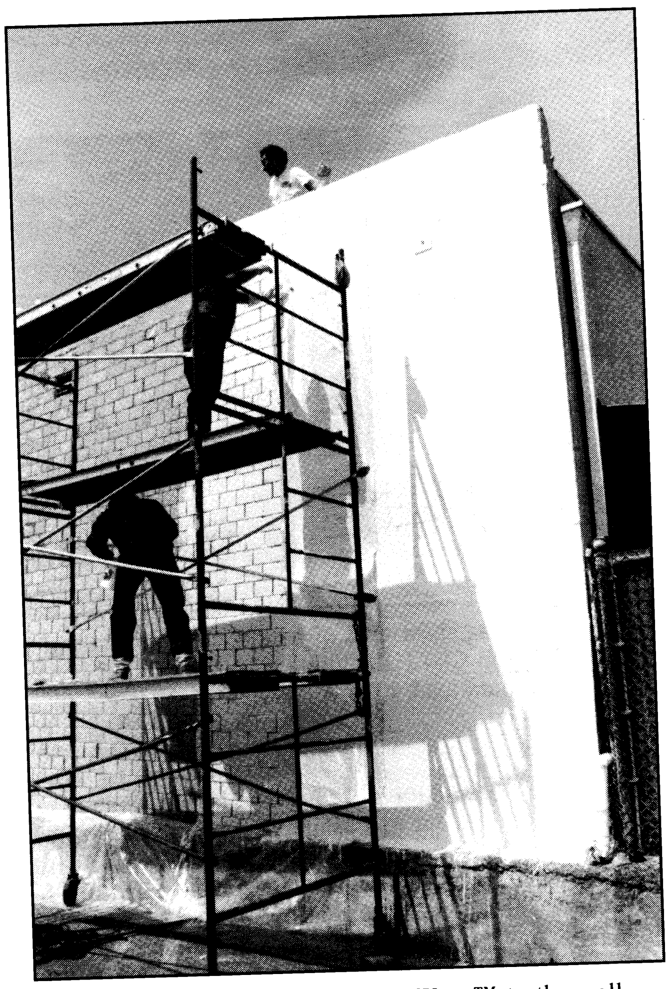

Fig. 12—Application of *QuakeWrap*™ to the wall *(Photo courtesy of External Reinforcement, Inc.)*

CONCLUSIONS

The test results indicate that retrofitting of unreinforced masonry structures with composite fabrics is a very effec-

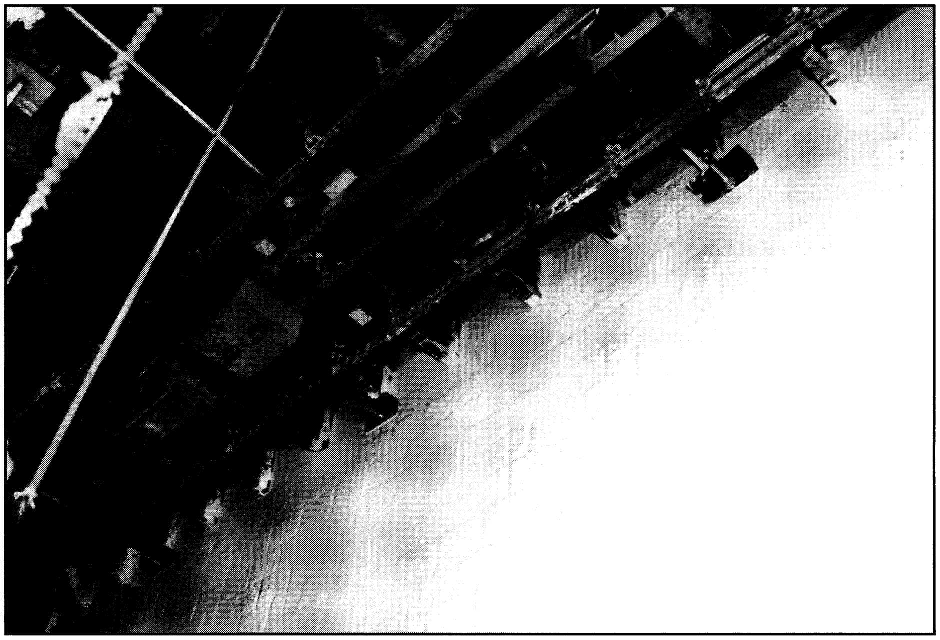

Fig. 13—Interior of wall at ceiling *(Photo courtesy of External Reinforcement, Inc.)*

Fig. 14—Exterior of wall at completion of project *(Photo courtesy of External Reinforcement, Inc.)*

tive technique for increasing the flexural and shear strength and ductility of these elements. The retrofitted beams could resist loads as high as twenty four times their weight and exhibited deflections of up to 1/48 times the span. The shear specimens also carried significantly high loads and failed in a ductile manner. Similar to reinforced concrete structures where the mode of failure is governed by the amount of the reinforcement provided, in these applications the strength of the fabric controls the mode of failure. Assuming that the epoxy does not fail prematurely when lighter fabrics are used, the maximum load is that causing tension failure of the fabric. When heavier fabrics are used, the fabrics maintain the integrity of the wall until the masonry units reach their maximum strength.

The application of *QuakeWrap*™ in repairing the building that was severely damaged during the Northridge earthquake provided a unique economical solution for the retrofitting of the wall. Considering the ease of application, the improved structural behavior which results, and the lower cost, the technique provides a unique viable alternative for seismic retrofitting of unreinforced masonry structures.

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