Application of Stability-Based Retrofit Measures on Some Historic and Older Adobe Buildings in California

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Abstract: *Recent earthquakes in California, including the San Simeon earthquake of 2003, have resulted in losses and serious damage to California's earliest and most culturally significant buildings, its historic and older adobes. As destructive as these earthquakes were, they have provided opportunities for engineers concerned with historic preservation to study the types of damage that occur to soft (unburned earth) masonry buildings as a result of significant ground shaking.*

In addition to a damage survey of historic adobes following the Northridge earthquake of 1994, testing of adobe structural models on the shake tables at the University of California, Berkeley (UC Berkeley), and Stanford University were carried out in the 1980s by the National Science Foundation and in the 1990s through the Getty Seismic Adobe Project (GSAP), to duplicate many of the types of damage observed in the field and to determine the efficacy of various stability-based methods of retrofitting unreinforced adobe buildings. These stability-based methods limit relative displacement between elements of the structure and use gravity as a restoring force. Stability-based retrofitting is seen to be less invasive to the historic fabric than is strength-based retrofitting, and it is sensitive to both life-safety performance and the requirements of historic preservation.

As California state law and local building code ordinances have been enacted in recent years to address the problem of strengthening of unreinforced masonry (URM) buildings, the application of stability-based retrofit measures to historic and older adobes has been gaining acceptance by both historic preservationists and building officials. This paper briefly discusses the development of stability-based retrofit measures, as developed by GSAP, and presents four examples of recent rehabilitated historic and older adobes in California with seismic retrofits based on these concepts.

Introduction

California's historic and older adobe buildings pay a heavy toll during large earthquakes. Events, such as the Loma Prieta (1989) and Northridge (1994) earthquakes, as well as the more recent San Simeon (2003) earthquake, were no exceptions. In fact, the Northridge earthquake resulted in the greatest loss to California historic and older adobes since the 1925 Santa Barbara earthquake.

Starting in the 1970s, interest in the preservation and rehabilitation of California's historic and older adobes yielded various attempts to use structural engineering concepts to design seismic retrofit measures appropriate for historic adobes. Prior to the development of codified regulations in the form of the California Historical Building Code (CHBC) (California Building Standards Commission 1998), first printed in 1979 and made mandatory in 1985, guidance for seismic retrofitting was frequently sought from the Uniform Building Code (UBC) (International Conference of Building Officials 1979). Since adobe is not recognized in the UBC as having the potential for seismic load resistance, basing retrofit design on the UBC resulted in rather heavy-handed interventions, such as independent steel or reinforced concrete structures designed to carry roof, ceiling, and floor loads. These independent structures, in the form of added shear walls or structural frames, were overly disruptive to the historic fabric and removed the stabilizing gravity loads from the tops of the historic adobe walls. Introduction of the CHBC had a dramatic effect on the philosophy of seismic rehabilitation of historic adobes. It is a code that sets safety standards while recognizing the unique qualities and importance of historic structures, and it explicitly recognizes the inherent strength of extant adobe walls that have withstood the test of time. The CHBC allows:

1. engineering judgment in the evaluation of strength and performance based on historical evidence;
2. use of maximum height-to-thickness ratios for one- and two-story structures, in lieu of a more complete out-of-plane wall analysis;
3. a maximum shear stress of 4 psi (0.28 kg/cm^2).

However, the early versions of the CHBC (1979–90) also required a reinforced concrete bond beam at the top, interconnection of all walls, and a minimum depth of 6 in. (15 cm) and width of 8 in. (20 cm). This limited choice and definition of a bond beam, as well as limits on height-to-thickness ratios, spurred further research, testing, and field surveys in the mid 1980s and throughout the 1990s. Sponsored first by the National Science Foundation (1980s) and later by the Getty Conservation Institute (1990s), much of this research involved review of previous testing efforts in Mexico (Meli, Hernandez, and Padilla 1980) and Peru (Vargas N. et al. 1984), as well as review of previous efforts at developing seismic retrofit measures for historic adobes in California (Thiel et al. 1991).

Shake table testing of adobe model structures has been carried out at both UC Berkeley's Richmond Field Station (Scawthorn and Becker 1986) and Stanford University's John Blume Center in the 1980s (Tolles and Krawinkler 1990), with additional shake table testing during the 1990s at Stanford University and at the Institute of Earthquake Engineering and Seismology in Skopje, Republic of Macedonia (Tolles et al. 2000).

Field studies of the condition and performance of historic and older adobes have been an ongoing activity since 1987, subsequent to the Whittier Narrows earthquake, continuing in 1989 following the Loma Prieta earthquake, and through to the present. A significant Getty Conservation Institute reconnaissance survey effort was carried out in 1994 following the Northridge earthquake (Tolles et al. 1996). Recently, damage to historic adobe structures due to the San Simeon earthquake of 2003 was investigated by the author.

Although adobe structures are often vulnerable to earthquake shaking, it has been observed that some adobes have performed well during past earthquakes and that specific types of damage can be expected to occur during earthquakes. Shake table testing has shown that with the introduction of simple stability-based retrofit measures, these structures can perform well during large earthquakes.

Observed Seismic Performance of Adobe

Estimates of Modified Mercalli intensity (MMI) and peak ground acceleration (PGA) at each of twenty historic and nine older adobe sites included in the Northridge earthquake survey (Tolles et al. 1996) were determined based on volume 1 of the Earthquake Engineering Research Institute (EERI) reconnaissance report (Hall 1995), California Strong Motion Instrumentation Program (CSMIP) station data (Shakal et al. 1994), and the preliminary report of the Earthquake Engineering Research Center (EERC) at UC Berkeley (Stewart 1994).

To correlate damage with intensity, damage state definitions were adopted from EERI and modified specifically for historic and older adobes. Damage state definitions were developed by EERI for the purpose of comparing relative damage levels in unreinforced brick masonry buildings. Table 1 lists damage states A through E along with their descriptions. The table also includes commentary on these damage states relative to the specific behavior of historic and older adobe buildings. Overall seismic performance of each adobe was rated during the survey.

Figure 1 is a plot of damage versus peak ground acceleration for unreinforced, well-maintained historic and older adobes (sixteen out of the twenty-nine surveyed). These buildings had insignificant preexisting conditions; thus, adobes were excluded that had unrepaired or poorly repaired preexisting crack damage, severe water intrusion damage, or previous retrofits or upgrades. Figure 1 also includes a linear least-squares relationship ("best estimate") of damage as a function of PGA, which serves as a baseline for judging the performance of adobes that either suffered from or were enhanced by preexisting conditions. Even though con-

Table 1 Earthquake Engineering Research Institute (EERI) standardized damage states

Damage state	EERI description	Commentary on damage to historic and older adobes
A (0)[1] None	No damage, but contents could be shifted. Only incidental hazard.	No damage or evidence of new cracking.
B (1) Slight	Minor damage to nonstructural elements. Building may be temporarily closed but could probably be reopened after minor cleanup in less than 1 week. Only incidental hazard.	Preexisting cracks have opened slightly. New hairline cracks may have begun to develop at the corners of doors and windows or at the intersection of perpendicular walls.
C (2) Moderate	Primarily nonstructural damage; there also could be minor but nonthreatening structural damage. Building probably closed 2 to 12 weeks.[2]	Cracking damage throughout the building. Cracks at the expected locations, and slippage between framing and walls. Offsets at cracks are small. None of the wall sections are unstable.
D (3) Extensive	Extensive structural and nonstructural damage. Long-term closure could be expected due either to amount of repair work or uncertainty on feasibility of repair. Localized, life-threatening situations would be common.	Extensive crack damage throughout the building. Crack offsets are large in many areas. Cracked wall sections are unstable; vertical support for the floor and roof framing is hazardous.
E (4) Complete	Complete collapse or damage that is not economically repairable. Life-threatening situations in every building of this category.	Very extensive damage. Collapse or partial collapse of much of the structure. Repair of the building requires reconstruction of many of the walls.

[1] An arbitrary numerical is included for the purpose of plotting damage state data versus ground shaking intensity.

[2] Times are difficult to assign because they are dependent on many factors, including building size.

siderable scatter is evident, some trends are reasonably clear. It appears that PGA in the range of 0.1–0.2 g is needed to initiate damage in the well-maintained adobe buildings. At this level of shaking, cracks will begin to form at door and window openings and at the intersections of perpendicular walls. At a PGA of about 0.4 g, the damage is moderate to extensive and includes more general crack damage throughout the structure.

Figure 2 is a plot of damage level versus PGA for those adobes with the preexisting conditions (thirteen

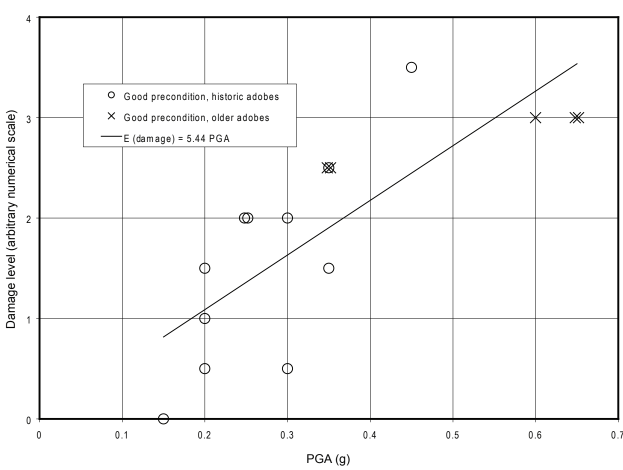

FIGURE 1 Northridge earthquake damage versus peak ground acceleration (PGA) for historic and older unreinforced and well-maintained adobes.

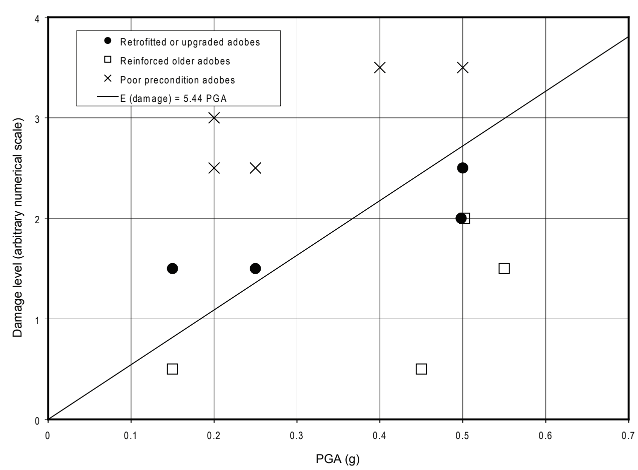

FIGURE 2 Northridge earthquake damage versus peak ground acceleration (PGA) for adobes other than unreinforced and well maintained.

out of twenty-nine surveyed). Relative to the "best estimate" for unreinforced, well-maintained adobes, preexisting conditions have definite effects on the resulting damage states. Obviously, adobes in a poor precondition state fared worse than those that were well maintained. Even at moderately intense ground shaking (0.1–0.2 g), poorly maintained adobes suffered substantial damage. Another trend observed is that reinforced older adobe buildings show greater resistance to damage than the unreinforced, well-maintained adobes at all levels of ground shaking.

Not so obvious, because of the sparse data, is the effect that seismic retrofits or upgrades have on the performance of historic and older adobes. A preliminary conclusion from figure 2 might be that the value of seismic retrofitting or upgrading is not realized until relatively high levels of ground shaking (i.e., above 0.3 g). At lower levels of ground shaking, the retrofit measures do not appear to affect performance. At these lower levels, the retrofitted buildings behave much the same as unreinforced, well-maintained adobes. Similar performance has been observed during shake table tests (Tolles et al. 1993; 2000).

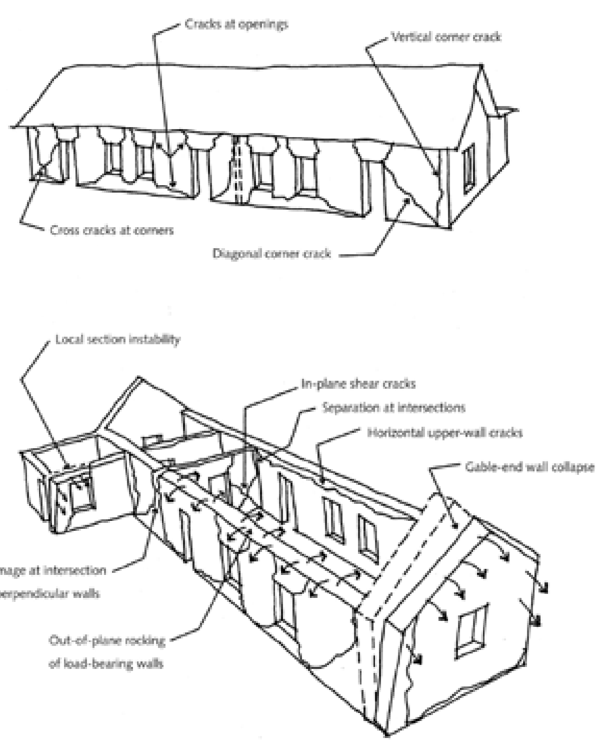

FIGURE 3 Types of damage observed in historic and older adobe buildings. (Reproduced from Tolles et al. 1996, 20.)

Damage Typologies

Designation of standardized damage states is useful in seismic risk studies or for insurance purposes. However, designing effective stability-based retrofits requires knowledge of specific types of damage. Based on field reconnaissance surveys, the types of damage observed that influence the overall seismic performance of historic and older adobe buildings are shown in figure 3.

Out-of-Plane Flexural Damage

Out-of-plane damage is initiated as vertical cracks that form at the intersection of perpendicular walls. These cracks extend downward or diagonally to the base and run horizontally along the base between transverse walls. During an earthquake, walls rock out of plane, rotating about the horizontal crack at the base. As a consequence of out-of-plane wall motion, longitudinal walls pull away from the transverse walls. In many cases there is no physical connection at the intersection of longitudinal and transverse walls, because the walls were constructed by simple abutment.

Gable-wall collapse is a special case of out-of-plane flexural damage. Gable walls are taller than longitudinal walls and usually are not well supported laterally. Unless anchored to the roof diaphragm, they can slip out from underneath roof framing.

Mid-height horizontal cracking is another special case of out-of-plane flexural damage, and it affects long, tall, and slender walls. Crack damage from this type of out-of-plane movement may not be serious in and of itself, but it signifies the potential for much greater and more serious damage—i.e., buckling of the wall and collapse of the roof.

Slippage of the top plate and/or displacement of the top courses of adobe blocks are other results of the out-of-plane movement of longitudinal walls. Very limited friction is generated by the dead weight of the roof bearing on the wall, and because of the friable nature of the top of the walls, slippage may occur.

Finally, vertical cracks on two perpendicular wall faces at a building corner caused by rocking of one or both walls results in a freestanding wall column at this location that is quite vulnerable to overturning and collapse.

In-Plane Diagonal and X-Cracking

Diagonal and x-cracks result from shear forces in the plane of the wall. These cracks are generally not serious unless the relative displacement across the cracks is large. These cracks represent a lessening of in-plane lateral stiffness, but unless a segment of wall on one side of the crack is in danger of losing purchase on the adjacent segment, such as at or near a corner, the gravity load path remains intact. Diagonal cracks also occur at the stress concentrations at the corners of doorways and windows and result from PGA levels as low as 0.1–0.2 g.

Moisture Damage

Although not the result of earthquake ground shaking, moisture in adobe walls does affect the seismic performance of the walls. This includes excessive spalling of plaster and adobe as the wall rocks out of plane, instability caused by basal erosion that removes material at the base of the wall, and/or reduced wall strength from repeated wet-dry cycles or rising damp. If the base of the wall is wet during ground shaking, a through-wall slip plane may develop along which the upper portion of the wall can slip, collapse, and overturn.

Stability-Based Retrofits

Field observations of damage to historic and older adobes and shake table testing of various stability-based retrofit measures clearly suggest that these structures can perform well during large earthquakes. The principal goals of a stability-based retrofit system (see table 2) are to:

1. provide structural continuity by interconnecting all walls with a bond beam or continuity hardware at the top of the walls;
2. prevent out-of-plane overturning of walls with horizontal straps (including bond beam or continuity hardware) and/or vertical straps or center core rods interconnected with the bond beam or top-of-wall continuity hardware; full or partial diaphragms with top-of-wall anchorage are also included;
3. contain the wall material by limiting the relative displacement across cracks or potential cracks of adjacent wall elements. Relative displacement of adjacent elements may be limited either by local ties between elements or by applied surface mesh with through-wall ties.

Table 2 Stability-based retrofitting goals and measures for some recently retrofitted historic and older adobes

Stability-based system goal	Stability-based measure
Structural continuity at floor and roof/ceiling	Existing bond beam interconnecting all walls
	Top-of-wall continuity hardware (straps, cables), through-wall tied
	Miscellaneous continuity hardware (connecting discontinuous existing bond beam elements)
Out-of-plane overturning stability	Top-of-wall pins (steel or fiberglass)
	Vertical center core rods (steel or fiberglass)
	Diaphragm (partial or full)
	Top-of-wall anchorage
	Through-wall floor anchorage
Containment of wall material	Horizontal and/or vertical straps or cables, through-wall tied
	Horizontal and/or vertical center core rods
	Surface mesh, through-wall tied
	Top-of-wall continuity hardware, through-wall tied, in conjunction with top-of-wall pins

Stability-based measures do not stiffen the structure in any significant way. In fact, they do not come into play until old cracks reopen and the structure has developed some new cracks and has moved enough to engage the stabilizing elements. These measures, however, provide reduction in the response of the building in at least two ways: (1) by increasing the structural damping due to friction hysteresis across the cracks; and (2) by lowering the response frequency due to wall rocking.

A short list of some historic and older adobes in California for which stability-based measures have been designed and utilized is presented in table 3, which includes the stability-based elements used to achieve the three stability-based system goals. The following is a discussion of three of these examples.

Table 3 Specific stability-based system measures to promote structural continuity, restrain overturning, and contain wall material for some California historic and older adobes (N = new; E = existing)

Structure name/location	Structural continuity	Overturning restraint	Wall material containment
Shafter Courthouse (1992) Shafter, CA	(N) misc. continuity hardware to connect (E) discontinuous bond beam elements	(N) top-of-wall fiberglass vertical pins; (E) bond beam and diaphragm	(E) and (N) wire stucco mesh; (N) through-wall ties with oversize washers
Lydecker Adobe (1992) Aptos, CA	(N) misc. continuity hardware to connect (E) discontinuous bond beam elements	(N) steel diagonal top-of-wall pins; (E) bond beam and diaphragm	(E) horizontal rebar
O'Hara Adobe (1994) Los Angeles	(N) steel top-of-wall and misc. continuity hardware	(N) top-of-wall vertical pins; (N) top-of-wall anchorage; (E) diaphragm	(E) and (N) wire mesh containment; (N) through-wall ties and oversize washers
Salvador Vallejo Adobe (1998) Sonoma, CA	(N) steel-strap top-of-wall continuity hardware	(N) center core vertical rods; (N) top-of-wall and through-wall floor anchorage	(N) wire mesh on select walls; (N) through-wall ties and oversize washers on walls with wire mesh
Leese-Fitch Adobe (1998) Sonoma, CA	(E) bond beam; (N) top-of-wall continuity hardware	(N) center core vertical rods; (N) top-of-wall and through-wall floor anchorage	(N) wire mesh on select walls; (N) ties from center core rods to wire mesh
Mission San Miguel (2005) San Miguel, CA	(N) top-of-wall continuity hardware	(N) steel top-of-wall vertical pins; (N) diaphragm; (N) top-of-wall anchorage	(N) top-of-wall strap, through-wall-tied and vertical top-of-wall pins

Shafter Courthouse

Background

The Shafter Courthouse, in Shafter, California, is an adobe structure built in 1940 by the Works Progress Administration (WPA). It is typical of many that were constructed in California during the 1930s and 1940s by the WPA. It is a well-built, one-story building with an L-shaped plan. The building was given to the City of Shafter by the County of Kern in 1992, and the city council decided to rehabilitate it for use as the new city hall.

A significant test of the seismic capability of this structure occurred during two earthquakes in 1952. Shafter is located in a seismically active area, heavily influenced by the proximity of the San Andreas, Garlock, and White Wolf faults. Movement along the White Wolf was responsible for the damaging Kern County and Bakersfield earthquakes of 1952. The July 21, 1952, Kern County earthquake had a Richter magnitude of 7.7 and caused major damage to structures in towns southeast of Bakersfield. The August 22 aftershock had a Richter magnitude of 5.8 and caused major damage in Bakersfield, particularly to buildings already weakened by the earlier quake. As a result of either or both of these earthquakes, slight damage occurred to the courthouse adobe, primarily at the bond beam level.

Building Description

Wall thickness of the courthouse adobe ranged from 12 in. to 24 in. (30–60 cm). Wall heights varied from 10 ft. to 12 ft. (3.0–3.7 m), with gable walls extending up another 3 ft. (0.9 m). Height-to-thickness ratios varied from approximately 5 to 7, a relatively stable configuration. A series of adobe piers on the inner face of the L formed an enclosed corridor. All wall surfaces except the interior corridor were rendered with stucco over galvanized-wire stucco lath.

The building was constructed with reinforced concrete bond beams, from 5 in. to 8 in. (13–20 cm) deep and as wide as the wall thickness. Bond beams at different elevations were discontinuous at wall intersections. The roof framing and top plate were bolted to the bond beam.

Stability-Based Retrofit Measures

Although the courthouse adobe was not seriously damaged in the 1952 earthquakes, there were clear signs of distress at the discontinuities of the bond beam. Three stability-based retrofit measures were utilized in this project:

1. continuity hardware at discontinuous bond beams
2. bond beam anchorage to walls
3. use of wire mesh as containment

Miscellaneous continuity hardware in the form of steel straps and brackets was used to tie the bond beams together at various levels. Tube steel posts were used to anchor discontinuous bond beam elements to continuous bond beam elements at a different elevation, as well as to the foundation (fig. 4).

The concrete bond beams were anchored to the tops of the walls, including the gable walls, by drilled-in 1 in. (2.5 cm) diameter fiberglass rods that penetrate through the concrete and into the top courses of adobe block to a depth ranging from 2 ft. to 3 ft. (0.6–0.9 m). These rods were grouted in place with a fly-ash/soil mixture, which had been used on other historic adobe retrofit projects in California (Roselund 1990).

Since most of the wall surfaces were already rendered with wire mesh and stucco (with no signs of adobe deterioration), it was decided to cover the remaining surfaces with wire mesh and stucco, and to through-tie all new and existing stucco mesh with all-thread rods and oversize washers. This system acts as a containment of the adobe; it does not permit blocks or pieces that crack to fall out of the wall during ground shaking, thereby assuring a continued load path.

The rehabilitated courthouse adobe was dedicated as the new Shafter City Hall in August 1992.

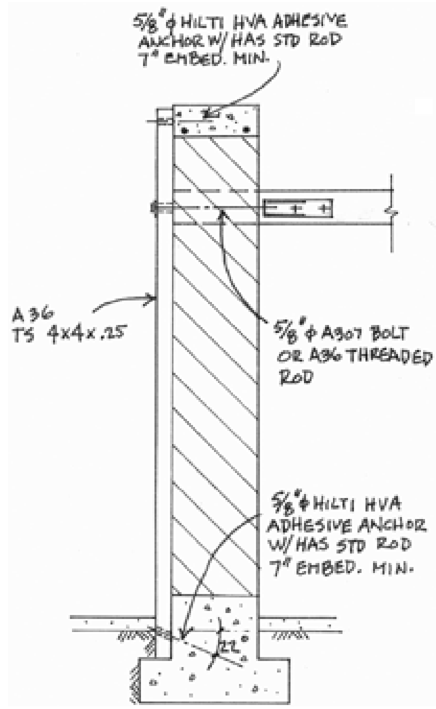

FIGURE 4 Typical wall section of the Shafter Courthouse, showing continuity hardware interconnecting discontinuous bond beams.

O'Hara Adobe

Background

The unreinforced O'Hara Adobe was built in the Toluca Lake area of Los Angeles just after the Long Beach earthquake of 1933. The main adobe structure is 34 × 80 × 13.5 ft. (10.4 × 24.4 × 4.1 m) high, and it has gable walls that extend to 18 ft. (5.5 m) tall. This great room features an adobe tower structure 11 × 12 × 18 ft. (3.4 × 3.7 × 5.5 m) tall. The original plan was to construct a much higher tower, so that the entire building would mimic mission-style architecture. However, following the Long Beach earthquake, building authorities would not allow such a tall adobe tower, so it was constructed to match the height of the roof ridge.

The walls were measured at 3 ft. (0.9 m) thick, and they had what was thought to be a relatively stable height-to-thickness ratio. Yet, during initial retrofit activity, it was discovered that the walls of the great room were actually two single-wythe, 12 in. (30 cm) thick walls with a 12 in. (30 cm) air gap between them. Thus, the height-to-thickness ratio was actually 13.5, not 4.5, as originally assumed. A height-to-thickness ratio of 13.5 is a relatively unstable wall configuration unless the wall is confined. It was decided, then, to fill the 12 in. (30 cm) gap with a urethane-type foam (3 lb./ft.^{3}, or 48 kg/m^3) to within 2 ft. (61 cm) of the bottom of the existing bond beam. The remaining 24 in. (60 cm) were filled with super-lightweight concrete (70 lb./ft.^{3}, or 1121 kg/m^3).

The building has two adjacent low-rise wings with walls 12 in. (30 cm) thick and 8–10 ft. (2.4–3.0 m) tall. The exterior walls of the wings were capped with a concrete bond beam, while the interior cross walls, although closely spaced, had no bond beam.

Northridge Earthquake Damage

The O'Hara Adobe responded to the 1994 Northridge earthquake with typical adobe crack damage, but with little serious effect. The major damage was concentrated in the great room, where evidence of out-of-plane rocking of the massive north and south longitudinal walls was observed. Out-of-plane rocking damage was also observed in the east gable wall. Some of the observed crack damage appeared to consist of a reopening of preexisting cracks from earlier earthquakes.

New damage included a classic short-column, diagonal-shear crack that opened up in one of the adobe tower legs above the level where it abuts the cross wall of the mezzanine floor. One of four adobe chimneys was also damaged when the concrete cap slid and pushed off one side of the chimney above the roofline; the other three chimneys performed well during the earthquake. The building's two adjacent low-rise wings sustained no damage from the earthquake. These wings appeared to be quite stable, with several cross walls relatively closely spaced.

Stability-Based Retrofit Measures

The stability-based seismic retrofit design for the O'Hara Adobe was based on the nonprescriptive requirements of the CHBC, in particular the Alternative Structural Regulations section of the code. Structural upgrading was intended to encourage harmonic rocking response between parallel walls. The simple stabilization techniques that were utilized focused on structural continuity at the tops of the walls by providing steel straps to interconnect the intermittent concrete bond beam (a departure from the code-required installation of a continuous reinforced concrete bond beam), anchoring the walls to the existing roof structure with all-thread through-wall bolts, and connecting the existing plywood diaphragm sheathing to the fiberglass top-of-wall pins.

To completely confine the inner and outer wythes of the great room walls, stucco netting was added to the interior wall surfaces and through-tied with threaded rods and oversize washers to the existing stucco netting on the exterior surface, thereby providing a complete containment of the wall mass. The gable walls were also stabilized by anchoring them to the roof structure with fiberglass rods. Design of the fiberglass rods was based on a 0.8 W_p lateral force on the gable wall (W_p being the weight of the gable-wall section above the bond beam), and the design also took into account the stabilizing effect of the weight of the gable wall.

The tower leg that had suffered a short-column shear failure was stabilized by cutting a 4 in. (10 cm) gap in the mezzanine floor supporting wall where it abuts the tower leg, thus allowing the leg to rock freely, as did the other three legs. Steel plates to anchor through-bolts were added to this leg, to assure that it would respond in a rocking mode during future events.

The damaged chimney was dismantled and reconstructed with wood-frame and stucco construction starting at the bond beam level. Fiberglass rods were installed in the other chimneys to pin the concrete caps and ensure against sliding. The chimneys were also wrapped with stucco netting above the roofline for added confinement and stability.

In the two adjacent wings, where the cross walls had no bond beams, steel strap continuity hardware was installed to ensure that these walls were interconnected to the longitudinal wall bond beams, as well as to ensure that the exterior walls were positively supported by the cross walls.

All cracks were repaired with low-pressure mud grout injection.

Salvador Vallejo Adobe

Background

The Salvador Vallejo Adobe is a designated historical building in the city of Sonoma, California. The city's seismic upgrade ordinance of 1990 required the adobe to be evaluated and retrofitted in 1995 in accordance with the CHBC. Initially constructed of adobe in 1843 and then nearly twice as long as it is today, the building has been altered numerous times for commercial purposes and also because of earthquake damage sustained during the 1906 San Francisco earthquake. Wall thickness of the adobe ranges from 24 in. to 36 in. (60–90 cm) at the first-floor level and from 12 in. to 24 in. (30–60 cm) at the second-floor level. From first floor to second floor, the structure is 13.5 ft. (4.1 m) in height and another 11 ft. (3.4 m) to the second-floor ceiling, with height-to-thickness ratios ranging from 4.5 at the first-floor level

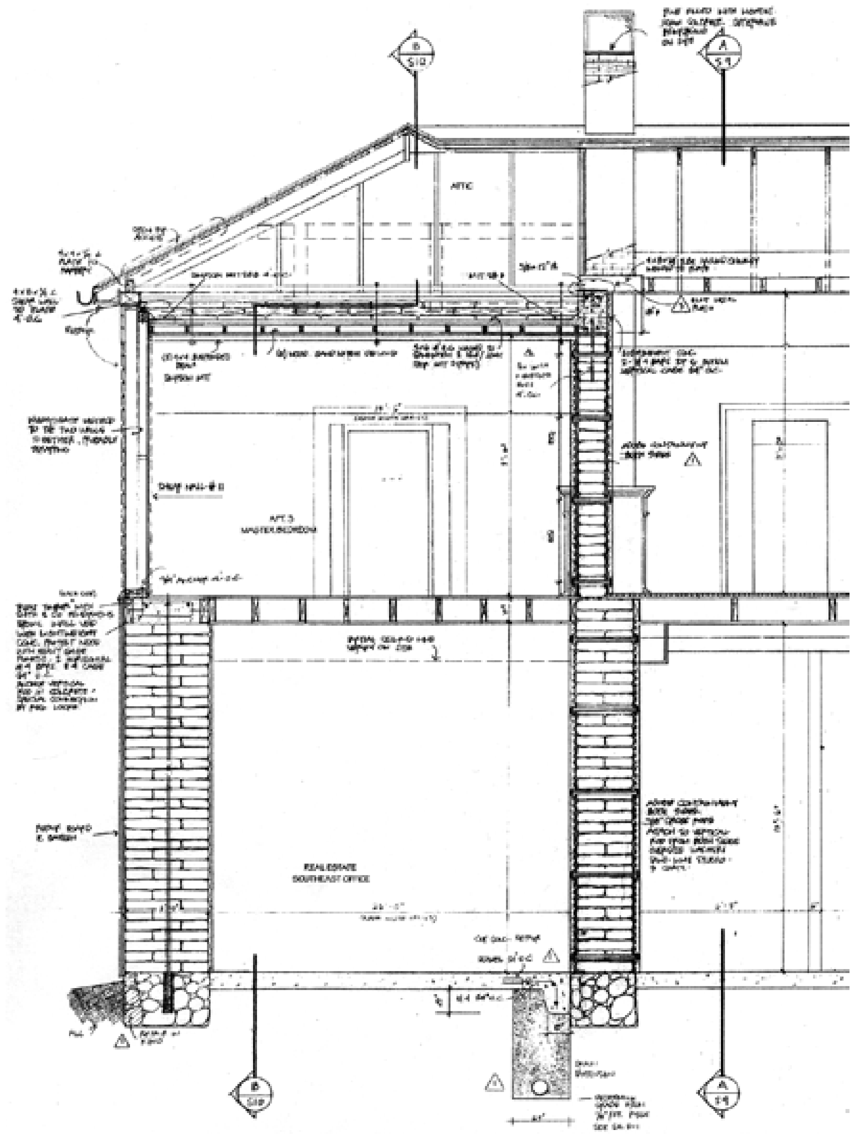

FIGURE 5 Salvador Vallejo Adobe wall and floor section, showing retrofit measures.

to 11 at one second-floor cross wall. A two-story wood-frame structure was added to the west side of the structure in about 1875. The second-floor adobe south wall was replaced with a wood-frame wall, probably as a result of damage caused by the 1906 earthquake.

Building Condition

No foundation settlement problems were observed. However, water damage to the adobe was evident, particularly at the bases of the west and east walls, where spalled adobe and bulging plaster could be seen. The south wall had serious coving damage resulting from rising damp. A few areas at the tops of the walls also showed erosion damage from roof leaks.

Crack damage could not be observed through the various wall coverings of plaster, shiplap boards, and board-and-batten siding on the exterior, and lime plaster and drywall on the interior. Many of the adobe blocks along the tops of the walls at the roof level are eroded, displaced, or loose, and the sill plate was not bearing on all of them.

Seismic Upgrade Measures

The initial concept for seismically stabilizing the Salvador Vallejo Adobe was to pin the tops of the walls with fiberglass rods and to anchor the tops of the walls to the horizontal bracing provided by the roof and second-floor framing. However, in the end, the walls were center-cored with steel rods extending the full height of the walls and epoxy-grouted into the footings (fig. 5). This change was based on the contractor's experience with center core techniques and his ability to convince the owner of the building to install the more expensive center cores.

The design also provided wall steel-strap continuity at the second floor and a lightweight reinforced concrete bond beam at the roof level. Roof and floor diaphragms were upgraded where necessary. Other seismic upgrade measures for the Salvador Vallejo Adobe included:

- French drains to mitigate surface water runoff
- welded wire mesh containment on the surface of the first- and second-floor adobe cross wall, with through-wall threaded rods and oversize washers

- reconstructed wood-frame shear walls in wood-frame addition
- bracing for the two chimney remnants that protrude above the roof, with steel straps and struts anchored to the roof structure

Mission San Miguel Gift Shop and Museum

Background

Mission San Miguel, the sixteenth mission in the chain of Spanish missions along the El Camino Real in Alta California, was founded on July 25, 1797, by Friar Fermín Lasuén. In 1816 the foundation stones for the existing church were laid; the building was ready for roofing in 1818. In addition to the church and sacristy structures that were completed in 1821, the present-day mission is made up of several large, single-story adobe buildings that form the quadrangle. Some date to the 1800s, while others were reconstructed in the 1930s and 1940s on original foundations and incorporated original wall material where it still existed.

The walls of the church are 156 ft. long, 30 ft. high, and 5.5 ft. thick (47.5 × 9.1 × 1.7 m). Walls of the quadrangle buildings, of which the gift shop and museum make up the southeast corner, are 10–15 ft. high and 2.0–3.5 ft. thick (3.0–4.5 m high and 0.6–1.1 m thick). A concrete bond beam was placed on the top of the long walls of the older buildings during a reroofing effort in the 1940s. The buildings that were reconstructed in the 1930s and 1940s have concrete bond beams at the top of both longitudinal and cross walls.

Earthquake Response

Since the completion of the church and sacristy in 1821, the mission has been subjected to frequently occurring earthquake tremors—the San Andreas Fault being quite close by. In 1857 a Richter magnitude 7.6 earthquake struck very close to the mission site, its epicenter just south of Parkfield, a distance of about 17 miles (27 km). The fault rupture was approximately 180 miles (290 km) in length, and it uplifted the area up to 30 ft. (9 m). Although scant information is available on the resultant damage to the mission structures, photographs taken at later dates (1882 through ca. 1900) indicate earthquake-type damage to portions of the church. Since 1857 the mission site has been subjected to numerous tremors of various levels of intensity, including aftershocks from the 1906 San Francisco earthquake that were centered near the mission.

In December 2003 the mission was damaged by the Richter magnitude 6.5 San Simeon earthquake. Immediately following the earthquake, the church and sacristy buildings were red-tagged by the County of San Luis Obispo.[1] A few of the buildings forming the quadrangle were yellow-tagged, while the remainder were green-tagged. However, in November of that year, the entire mission was shut down by the County of San Luis Obispo for noncompliance with the county's unreinforced masonry (URM) hazard mitigation ordinance, which requires that all URM buildings within the county be subjected to a structural analysis upon service of an order and within specified time limits. If a building is found not to comply with the ordinance's minimum earthquake standards, the owner is required to either demolish the building or structurally alter it to conform to the minimum standards. Time limits for developing conforming structural repair plans were not met, and a "Notice to Vacate" placard was placed on the mission. Therefore, in addition to seismic repairs, all the adobe buildings that form the mission (except for a novitiate built in the 1960s) are required to be seismically upgraded in accordance with the county URM ordinance in order to be permitted to reopen.

Stability-Based Upgrade Measures

Because of the critical issue of raising funds to accomplish the seismic upgrade, the repair and retrofitting efforts were split into phases that could be completed as funds became available. The phase 1 effort included the southeast corner of the quadrangle, which encompasses the gift shop and a portion of the museum. Since the friars of the mission rely on the proceeds from the gift shop and museum, it was the first area to be addressed, and the phase 1 buildings were reopened after completion in November 2005.

Stability-based measures utilized in the phase 1 retrofit effort included adding structural continuity at the ceiling level, supporting out-of-plane overturning stability, and containing wall material. Thin stainless steel straps that were through-wall-tied with stainless steel all-thread rods to a continuous ledger beam on the inside surface were installed at the tops of the walls, to serve as continuity hardware. The through-wall ties also acted as top-of-wall anchorage in conjunction with

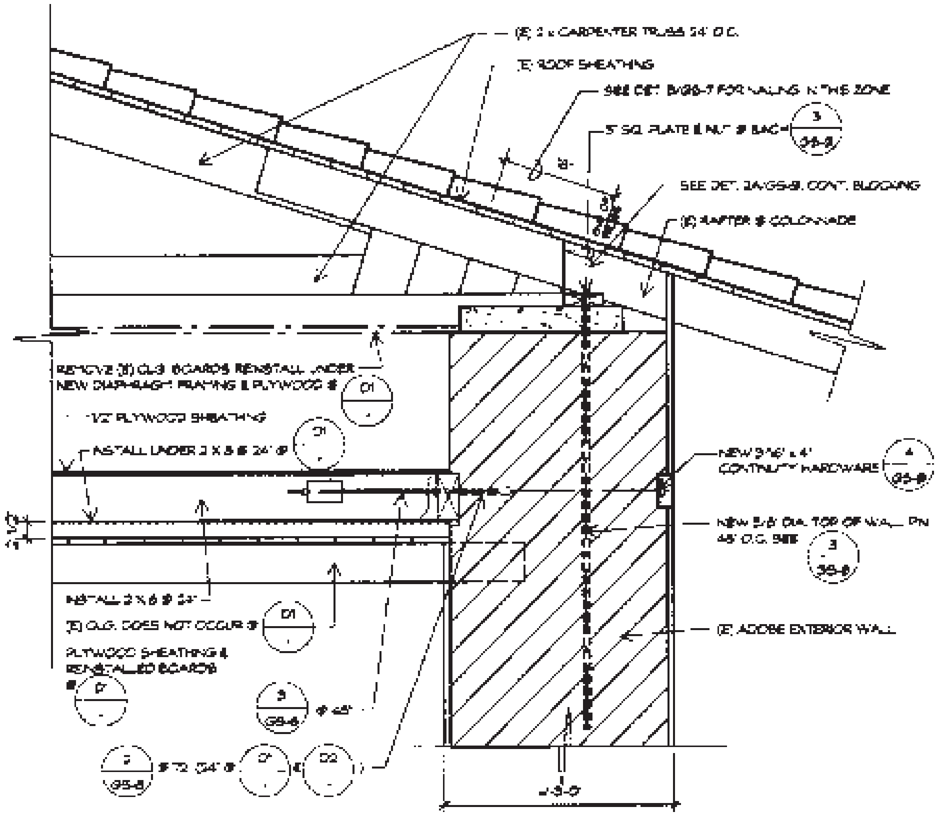

FIGURE 6 Typical top-of-wall stability-based measures for the Mission San Miguel gift shop.

a plywood diaphragm installed at or just above the ceiling level. Overturning stability was accomplished with stainless steel top-of-wall pins 3–4 ft. (0.9–1.2 m) on center, in conjunction with the top-of-wall continuity strap and diaphragm. Containment of the friable top courses of the wall was provided by the top-of-wall pins in conjunction with the top-of-wall continuity hardware, through-wall-tied to the ledger beam and diaphragm on the interior. Figure 6 shows a typical top-of-wall section and the stability-based measures utilized in this first phase of the Mission San Miguel seismic upgrade.

Conclusion

The information obtained during field studies of the seismic behavior and performance of historic and older adobes following an earthquake event is invaluable to the development of appropriate, cost-effective, and minimally intrusive stability-based retrofit measures (see Tolles et al. 1996 for more complete details on historic adobes). Categorization of the types of damage allows an evaluation of the causes and criticality of such damage types, so that effective retrofit measures may be developed and implemented. Indeed, this information, in conjunction with the shake table test results (Scawthorn and Becker 1986; Tolles et al. 2000), has been the basis for the design of appropriate seismic retrofit measures that ensure life safety while protecting historic fabric and cultural value.

The challenge of improving the structural and life-safety performance of historic and older adobes in future earthquakes, while saving historic fabric and cultural value in the process, is a great one. The key is to understand how these buildings perform and to direct minimal intervention and stability-based mitigation efforts to the specific needs and structural behaviors. We can, in fact, improve the performance of historic and older adobe buildings without significantly compromising their historic fabric or the architectural heritage embodied in these important resources.

Note

1 Following an earthquake, counties and cities in the affected area perform rapid safety evaluations of buildings in their jurisdiction, posting every building reviewed as either "Inspected" (i.e., apparently safe) or "Unsafe." Buildings posted Unsafe require repair or demolition, and they must be closed until such time as the appropriate repairs are complete. Buildings are posted as Unsafe with a red tag, as Inspected with a green tag, and as Limited Entry with a yellow tag. "Limited Entry" means simply that the building is off limits to unauthorized personnel, and further engineering evaluation needs to be performed before a red or green tag can be posted.

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