THE SEISMIC RETROFIT OF HISTORIC BUILDINGS CONFERENCE WORKBOOK

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RECENT DEVELOPMENTS IN UNDERSTANDING THE SEISMIC PERFORMANCE OF HISTORIC ADOBE BUILDINGS

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Getty Seismic Adobe Project

ABSTRACT

The purpose of this paper is to provide insights into understanding the seismic performance of adobe buildings. An acceptable approach to seismic retrofitting of historic adobe buildings must meet three distinct requirements: provide essential levels of occupant safety; preserve the historic fabric of the structure during the retrofitting process; and, provide acceptable performance in earthquakes. The work described is part of the Getty Conservation Institute's Guidelines for Seismic Strengthening of Adobe Project (GSAP). The initial phase of GSAP focused on examining existing knowledge and retrofit practice for adobes and on developing a philosophy of design to guide their seismic retrofitting. Results of this initial phase are summarized in this paper. It is argued that the seismic evaluation and retrofit design of buildings made of adobe should be distinctly different in both philosophy and detail from those used for conventional building materials. Conservation principles specifically applicable to historic adobes are discussed to establish the important conservation issues that must be respected when designing and applying a retrofit. Two engineering analysis approaches are assessed—the first is the conventional strength-based analysis procedure and the second is a stability-based approach. The stability-based approach is preferred because it can directly utilize adobe construction unique characteristics and explicitly addresses the collapse potential of these buildings. A summary of results of testing programs on adobe structures conducted at Stanford University and the University of California at Berkeley during the mid-1980s is presented and conclusions that are applicable to the seismic performance of historic adobes are given. Several retrofit designs that have been implemented during the last 15 years are assessed. Finally important design issues are discussed that need to be addressed in the seismic analysis and retrofit of adobe buildings. These provide a framework for understanding the seismic behavior and retrofitting of adobe buildings. Over the longer term, GSAP will undertake research and development efforts to supplement what is currently known and develop recommendations for seismic retrofitting of historic adobes.

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Introduction

Adobe is not a modern, conventional building material and adobe buildings should be differentiated from buildings made of other materials. California's historic adobe buildings were constructed starting at the end of the 18th century, with the majority completed by the middle of the 19th century. They were fashioned largely by Native American labor at the direction of Spanish colonists and their immediate descendants. Many adobes have survived major and moderate earthquakes, while others have suffered considerable damage. Typical damage to adobe structures during an earthquake can be classified as one of the following:

1. out-of-plane overturning of walls
2. in-plane shear cracking
3. separation of adjoining walls and
4. roof collapse which may result from a combination of the other three types of failure.

Some earthquake-damaged adobes have been repaired, but many damaged structures were simply abandoned.

The nature of adobe as a building material and the geometric configuration in which the material is used in construction make adobe structures a unique building type. Seismic retrofit strategies must consider the nature of adobe as a construction material and take advantage of their unique construction characteristics of adobe structures.

It is normal for adobes to be cracked from settlement or other natural causes and it is part of the historical tradition to repair these cracks. Adobes have typically had major additions and modifications, with the evolving configuration changing considerably over time. During moderate or higher earthquake ground motion most adobe buildings will suffer cracks. The repair of such damage is deemed permissible, since the repair and maintenance of such structures is an integral part of the historical tradition.

From an engineering perspective, the unique character of adobe buildings can only be fully utilized if they are allowed to crack during wall movement caused by an earthquake. In fact, it is virtually impossible to prevent adobe buildings from cracking. It is therefore imperative that the theoretical basis for an engineering analysis of retrofit measures include an understanding of the dynamic performance of cracked adobe buildings.

The principles of conservation hold that any intervention (retrofit in this case) should have minimal impact on the historic fabric of the structure. Conservation, in this context, is concerned with maintaining authenticity through the preservation and maintenance of materials and structural systems. Based on the evidence gathered to date—through testing and observed performance—the authors see no reason for conflict between conservation and life-safety issues. In many cases the approach to a seismic retrofit can preserve the historic fabric of adobe buildings, can minimize the risk of collapse and can reduce the extent of structural damage.

A portion of the work reported herein was performed as part of the Getty Conservation Institute's Guidelines for Seismic Strengthening of Adobe Project (GSAP). The goal of GSAP is to develop technical procedures and retrofit measures that, when implemented, improve the seismic performance of adobe buildings while respecting their cultural and architectural values. GSAP focuses on the Spanish Colonial Mission adobes and other historic adobes in seismic areas of California and the American southwest. GSAP as part of its initial phase has focused on examining existing knowledge and retrofit practice for adobes and developing a philosophy of design to guide their seismic retrofitting. Results of this initial phase are summarized in this paper.

Conservation Principles and Seismic Retrofitting

The importance of retaining the historic fabric of a building varies with the particular adobe, and depends on what treatment is appropriate for the particular building (i.e., stabilization, preservation, restoration, rehabilitation, reconstruction, etc.). A strictly conservation approach is concerned with fabric issues above all else. Obviously, many other considerations must be considered in historic preservation projects—life safety of occupants, continued use, and protection of contents. GSAP is exploring means to help retain the historic fabric of adobe structures while ensuring life safety, for occupants.

The most fundamental of conservation principles are to understand the object (building in this case) in context prior to intervention, to use the minimum intervention necessary, and provide reversibility and materials compatibility. This requires an almost encyclopedic multi-disciplinary knowledge of the structure and identification of all its cultural values and historic fabric at varying levels significance—data usually derived from the Historic Structure Report. In the seismic context this includes past seismic performance, microzonation and results of geotechnical site investigations. When such data are in hand, the principle of minimal intervention dictates that the least amount of alteration necessary to be used accomplish the task and safeguard authenticity—meaning, genuineness, not verisimilitude. Applying the conservation principal of reversibility allows for reversal or removal of interventions should they prove ineffectual, harmful, or inferior to methods developed in the future.

Structural stabilization and seismic retrofitting of historic adobe buildings typically have involved the sacrifice of traditional hand-crafted structural systems, portions of adobe walls, and extensive use of structural material that is incompatible with adobe. Concealment of retrofit measures (interventions) has been of paramount importance, contributing to rejection of the time-honored, visible fixes traditionally used (buttresses, tie rods, wall/joist anchors, cables). The imperative for concealment of structural interventions led to disregard for the cultural values of the adobe walls themselves and their component parts. Exclusive concern with architectural detail has led to the preservation of details at the expense of the whole in some instances—a phenomenon at variance with current conservation principles and practice.

A recent survey of adobe landmarks in California revealed less than a handful of structures where an additive or supplemental approach had been taken to structural stabilization. The overwhelming majority of those surveyed have been reworked with modern construction materials, neither supplementing nor replicating the early components in concept or detail. Little evidence of recording or salvage was found beyond HABS drawings completed as part of the WPA Depression era program.

Natural disasters, combined with rehabilitation and adaptive reuse, are taking a serious toll on adobe structures, California's earliest historic resources. J.N. Bowman identified some 900 adobe structures originally constructed in the San Francisco Bay area; today perhaps 60 survive, with more endangered by the recent Loma Prieta earthquake. An estimated 350 historic adobe structures of varying degrees of integrity remain in the entire state of California. It is imperative that the remaining few be protected not only from the risk of damage or destruction by seismic events, but also the certain hazard of inappropriate counter measures.

In recent years, the *State Historical Building Code (SHBC)* has initiated a move away from the excessive intervention prompted by the use of the *Uniform Building Code* for the seismic retrofit of adobes. The SHBC provides other acceptable retrofit approaches for treating materials and structural systems that would be considered either archaic or nonconforming under modern building regulations. Scientific investigation and respect for conservation concerns will hopefully combine to expand the options available for seismic retrofitting historic adobes, options which exploit rather than ignore the existing material properties—this is the ultimate goal of GSAP.

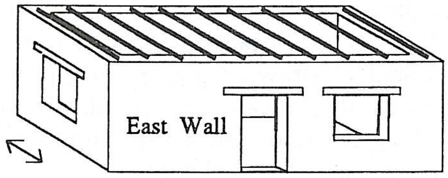
Seismic Response of Adobe Structures

Adobe masonry construction is a composite made from unfired clay bricks set in a mud mortar. The soil used for the bricks typically has a clay content that ranges from 10 to 30 percent to which an organic material, such as straw or manure, is almost always mixed before the blocks are formed. The organic material helps to reduce shrinkage and to distribute the shrinkage cracks as the blocks dry. The mortar is often composed of the same soil material as the bricks, but it may or may not contain similar organic materials. The mortar is almost always weaker than the bricks, since the bricks are dry when set in the wet mortar and shrinkage of the mortar is restricted by the dry bricks.

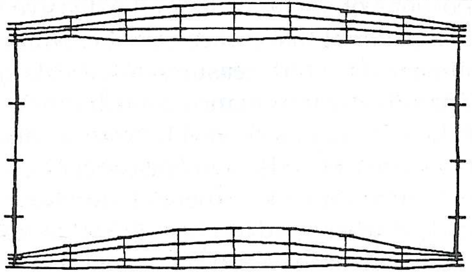
The behavior of adobe buildings can undergo significant changes during large seismic ground motions. While the building is undamaged, it will respond elastically and the dynamic behavior can be approximated using known analytical techniques. If the building is already cracked, then the limit of the applicability of elastic analysis is even lower, since Coulomb friction between elements along crack surfaces becomes important. Cracking is almost certain to occur during major seismic ground motions as the stresses in the walls exceed the tensile capacity of the adobe material. As cracks develop, the dynamic response characteristics of the structure undergo dramatic changes; the fundamental frequency decreases dramatically and the displacements increase by an order of magnitude or more. Motion along cracks becomes substantial as cracked surfaces intersect to form independent blocks of material. The dynamic behavior of a damaged adobe structure is not predictable using available analytical techniques; it can only be approximated empirically from tests and a general understanding of how damaged adobe buildings behave post elastically.

Elastic Behavior

The elastic behavior of most adobe structures is characterized by a relatively high frequency response and small structural distortion displacements. Even though the adobe material has a low modulus of elasticity (typically less than 100, 000 psi) compared to that of other building materials, the walls are usually quite thick and have relatively few openings. In tests performed at Stanford University (discussed in the section entitled "Recent Tests and Observed Behavior") the frequencies and mode shapes of a simple adobe test model were determined experimentally. With roof beams coupling the long walls, five modes of vibration were experimentally determined (Figure 1). The seismic performance was dominated by the first mode which had a frequency of 6.2 cycles per second (hertz) in the prototype domain. Larger adobe structures than those tested, such as Mission church buildings, will have lower fundamental frequencies in the undamaged state than those shown, but they will still be relatively high compared to the cracked condition.

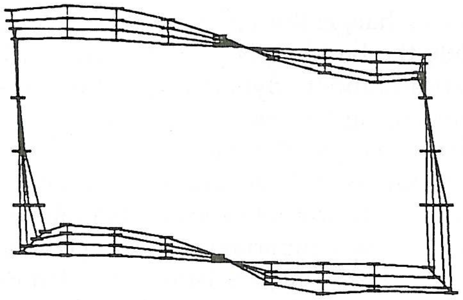


Model Adobe House with Anchored Roof Beams



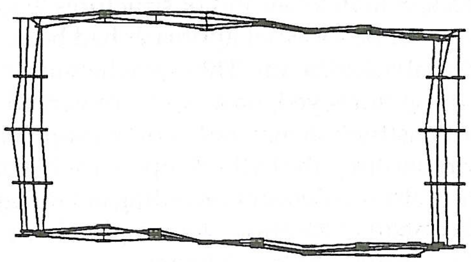
Mode 1 (6.2 hz.)

Transverse translation mode



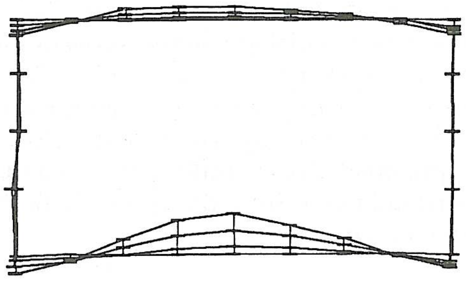
Mode 2 (9.8 hz.)

Torsion mode



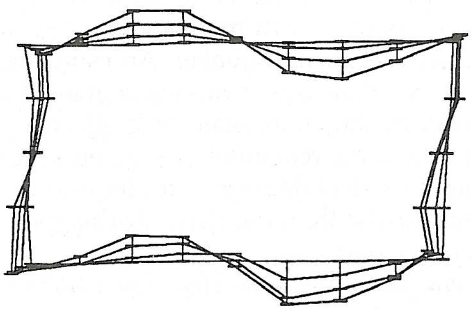
Mode 3 (11.2 hz.)

Longitudinal translation mode



Mode 4 (12.4 hz.)

Second order torsion mode



Mode 5 (20.8 hz.)

Second order breathing mode

Figure 1. Experimentally determined mode shapes and frequencies of a simple adobe house.

Initial Cracking

Substantial cracks nearly always exist in historic adobe buildings from past earthquake activity, and cracked walls are a typical feature of these buildings. Cracks develop in areas of high stress concentrations, including the corners of openings (doors and windows) the intersections of perpendicular walls and the base of walls (Figure 2). Cracks at doors and windows can develop from either out-of-plane (flexure) or in-plane (shear) forces in the walls. Cracks at wall intersections are typically a function of a combination of flexural and tensile stress, and can result in either vertical or diagonal cracks. The out-of-plane motion of long walls often results in horizontal cracking at the bottom of the wall, the vertical location of which is largely influenced by gravity loads induced by the weight of the wall or other tributary loads. In the massive adobe walls of Mission churches, this horizontal cracking may occur five or ten feet from the base of the wall. Cracks may also develop as a result of differential settlement of the foundation or differential creep or slumping within the walls themselves caused by moisture intrusion.

Thin adobe walls tend to be come unstable quickly upon initiation of cracks through the section, consistent with the observed behavior of other unreinforced masonry. However, a thick-walled adobe building is a long way from losing its stability when the first cracks in the wall develop. There must be many changes in the dynamic characteristics and much larger displacements before a thick wall approaches instability. Even if the engineer is unsure whether there are preexisting cracks, an adobe must develop substantial cracking before significant damage to the building can occur.

Changes in Dynamic Behavior

The dynamic characteristics of an adobe building change dramatically as cracks develop. For the out-of-plane motion of long walls, the effective frequency of motion decreases by a factor of 5 or 10, the wall accelerations decrease, and the structural distortion displacements increase. The term "effective frequency" is used to represent the apparent frequency of motion for a non-linear material. This change in behavior can be demonstrated by example from experimental data shown in Figures 3 and 4. The first two plots in Figure 3 show out-of-plane wall accelerations and displacements of the test building during a ground motion when damage was developing. About midway through the test, the wall accelerations began to decrease, the fundamental frequency was lowered, and the displacements began to grow dramatically. The third plot in Figure 3 shows the wall acceleration in the subsequent test. Even though the input motion is approximately 30 percent higher than that of the previous test, the peak wall accelerations have decreased throughout the test and the effective frequency has decreased.

The difference in out-of-plane wall displacements between damaged and undamaged buildings is best shown by a direct comparison of the out-of-plane displacements of a damaged and an undamaged building during the same test (Figure 4).

The displacements of the damaged building are nearly 10 times larger than those of the undamaged structure. The displacements shown in Figure 4 are still an order of magnitude less than required for overturning. Out-of-plane displacements of thick-walled adobe buildings can be quite large without threatening the stability of the walls.

In-plane wall displacements and accelerations un-

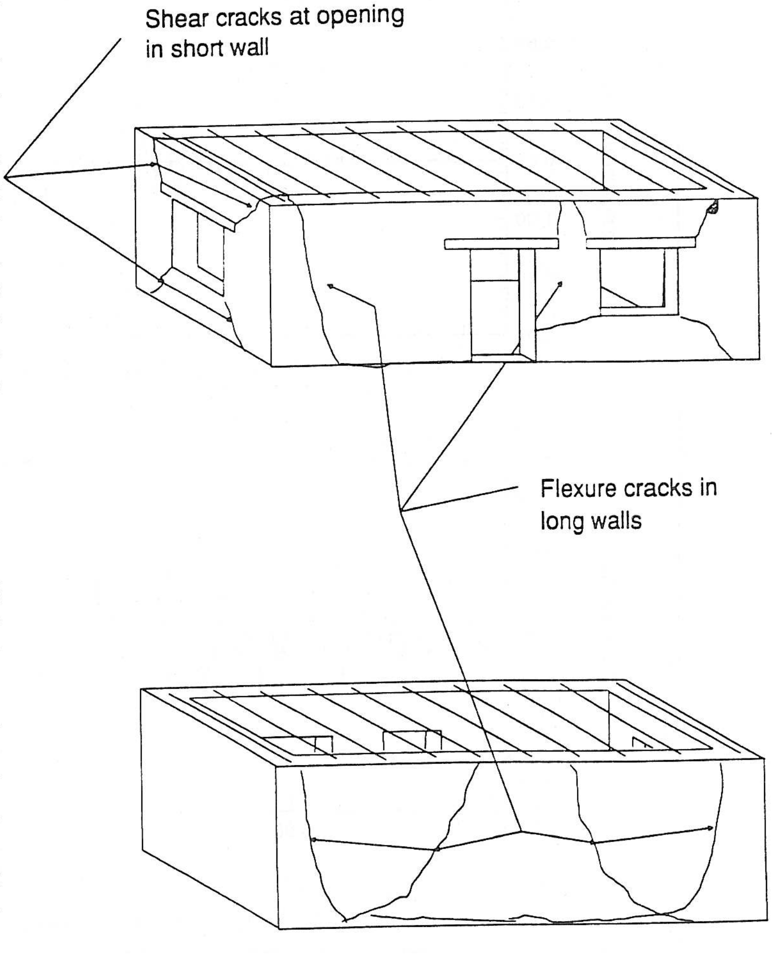


Figure 2. Initial Crack types in adobe buildings.

dergo less dramatic changes as cracks develop. In-plane wall displacements are usually not a threat to the stability of an adobe structure. As crack occur, friction across the cracks limits the in-plane wall displacements much more than it limits displacements in the out-of-plane direction. The limitation of in-plane wall displacements is usually more a desire for ease of repair than concern for stability. In some cases, however, when the cracks develop on a diagonal and there are no horizontal constraints on the

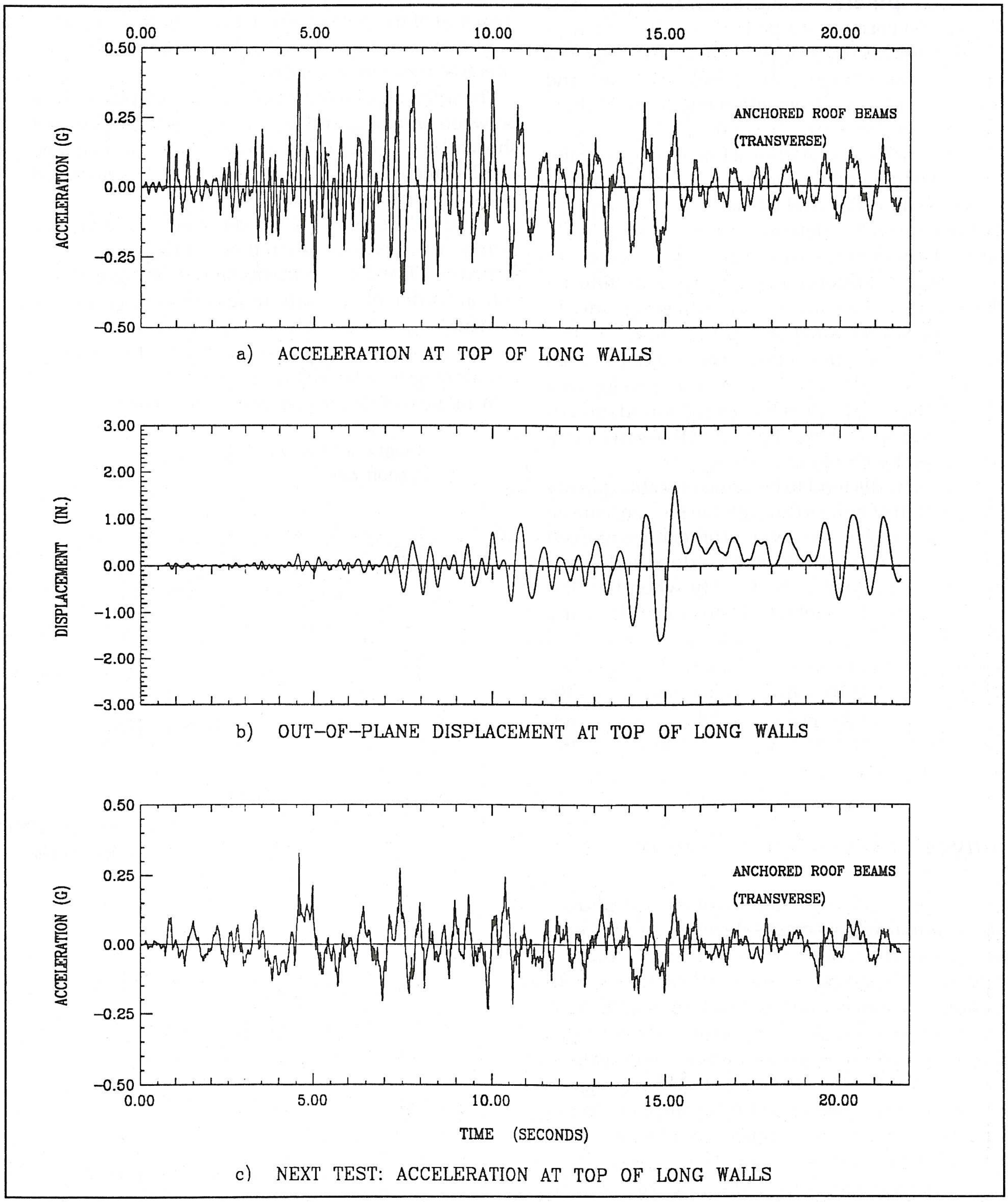
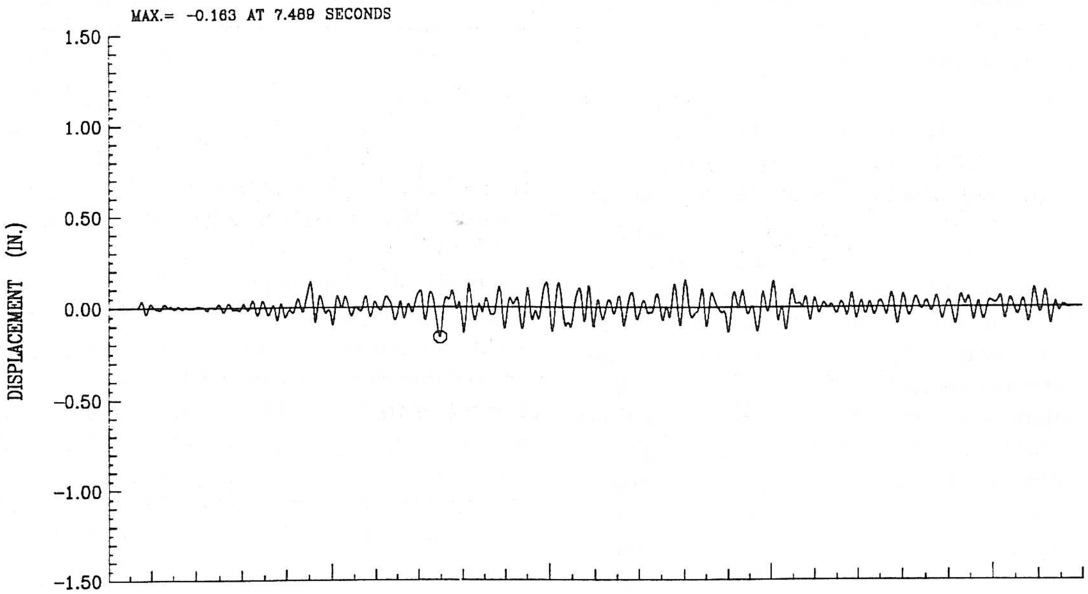
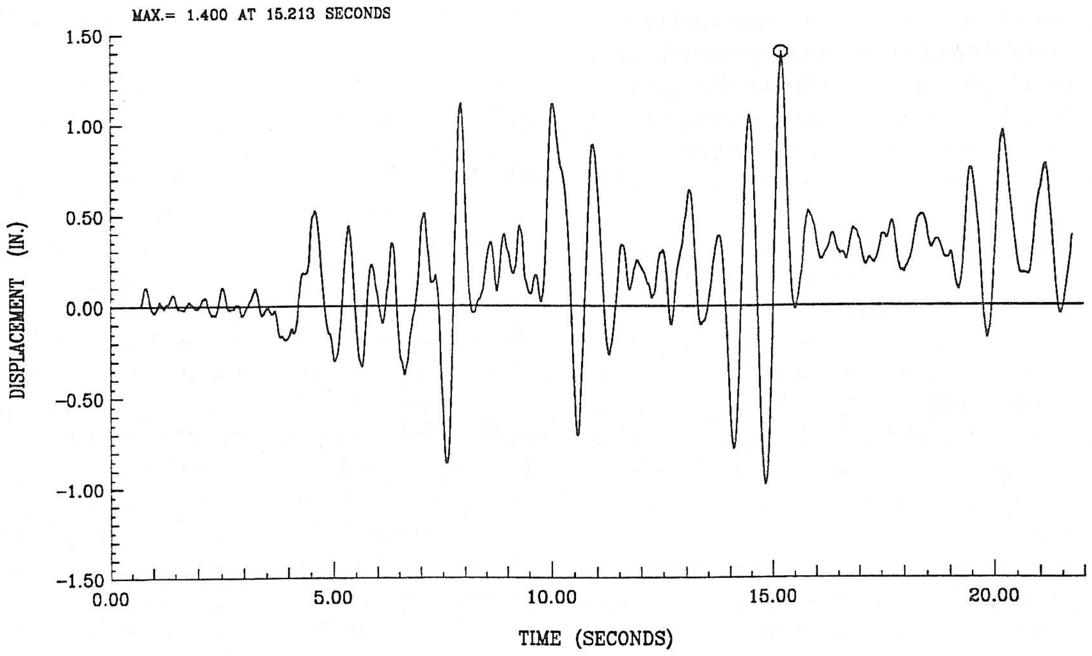


Figure 3. Decreasing wall accelerations as damage develops.

blocks in the walls, such as at building corners, continued shaking can allow gravity to work on the independent cracked blocks, which may lead to progressive in-plane or out-of-plane failure.



a) UNDAMAGED WALL



b) DAMAGED WALL

Figure 4. Out-of-plane displacements of damaged and undamaged walls.

Moderate to Heavy Damage and Collapse Potential

As damage to an adobe building progresses, crack size increases during reversing cycles of ground motion and the building's effective frequency continues to decrease. When the cracks fully develop, each wall becomes an assemblage of irregularly shaped wall segments (Figure 2) or broken adobe blocks. These blocks, referred to as "independent cracked blocks," may be a portion of the wall height or extend from one floor line to the next. In the horizontal direction, the independent cracked blocks may extend from one interior wall to the next or from opening to opening. Even though the building may have fully developed cracks and independent blocks of adobe formed from the intersection of these cracks, the structure is likely to still be able to sustain considerable ground motions without becoming unstable.

Out-of-plane wall displacements pose the largest collapse threat to an adobe building. Non-load bearing walls often are the first to collapse, particularly gabled end walls. The three primary factors that affect the out-of-plane stability (overturning) of badly cracked walls are (a) the absolute thickness and slenderness (height-to-thickness ratio) of the wall; (b) other restraints that may limit the deflection at the top (connection at the floor or roof line) or the sides (perpendicular walls) of each block formed in the wall; and, (c) added gravity loads from roof or floor framing. Vertical cracks may develop such that perpendicular walls provide little or no stabilizing effects. It should be noted that very little restraint (force) is required at the top of a block to substantially reduce the overturning potential of an independent cracked block.

Non-bearing walls, even though not as long as bearing walls, usually are the first to collapse because there is often little or no restraint provided by the roof or floor connections and no additional tributary loads. The hazard is particularly great for gabled walls simply due to their additional greater height-to-thickness ratio. Even though vertical bearing loads can help stabilize an out-of-plane wall, the key is restraint at the top of the wall, an attribute usually missing from non-bearing walls.

Bearing walls may also collapse, and the effect of their collapse is likely to be catastrophic from both a conservation and a life-safety perspective. For thick adobe walls with fully developed cracks, the length of the wall will have little effect on the overturning potential of that wall. A one hundred foot long wall with developed cracks at the bottom and sides may present no greater hazard of collapse than a fifteen foot long wall with similarly developed cracks. The primary factors affecting collapse of a bearing wall are its absolute thickness, its slenderness ratio, and the degree of restraint at the top. The longitudinal dimension of a wall, or an independent cracked block, may have little effect on its potential for overturning and collapse, unless the top of the wall is anchored to cross walls at the floor or roof level. Adequate connection between the walls and either the roof or flooring system is essential to prevent overturning. Inadequate bearing of roof or floor beams and the lack of a positive connection can allow a load bearing wall to progressively move out from under the beams.

In-plane shear damage to walls will worsen substantially during large seismic events. Diagonal cracks may develop in sections of the walls with no opening. The movement of wall blocks may be exacerbated by gravity and friction as the shaking continues. Broken segments near the ends of walls are susceptible to non-reversing sliding along diagonal cracks. The in-plane movement of blocks can be particularly problematic from the stand point of repair of damage to doors and windows and the difficulty (if not an impossibility) of returning these blocks to their original positions.

Recent Tests and Observed Behavior

The National Science Foundation, in the mid 1980s, sponsored shaking table tests of adobe structures at Stanford University and the University of California at Berkeley. These tests were performed to develop an understanding of the basic seismic performance and the relative seismic performance benefits of simple structural improvement (retrofit) techniques on low-strength masonry buildings. These are among the only major experimental programs on the seismic performance of adobe conducted in the United States.

More extensive experimental and testing programs have been performed at the Catholic University in Lima, Peru and at the National University of Mexico. The importance of these early testing programs cannot be overstated. The tests conducted in Mexico were the first shaking table tests conducted on adobe buildings and examined the relative benefits of a number of simple retrofitting schemes. The research conducted at the Catholic University in Peru is the most complete adobe research conducted top date anywhere in the world. The Peruvians have tested material strength, structural elements, and assemblages. Full scale adobe models have been tested on both a tilting table and a shaking table. The details of the Mexican and Peruvian research can be found elsewhere; only the Stanford and Berkeley tests will be discussed here.

Small-Scale Tests at Stanford University

The testing programs conducted at Stanford included six 1:5 scale models of a single room adobe house. Tests were conducted on the shaking table in the John A. Blume Earthquake Engineering Center. The shaking table is only capable of uniaxial motion. A drawing of the "prototype" building is shown in Figure 5. The six models tested are shown in Figure 6, including the model number and a brief description of the structural improvement technique. Model 1 is the "base" structure to which the improvements were added.

Each of the first five models were tested with the table motion perpendicular to the long walls. Model 6 was tested with the table motion parallel to the long walls. The table motion was based on the Taft N21E record of the 1952 Kern County earthquake. Each model was subjected to a series of tests in which the severity of the table motion was increased by approximately 30 percent over the previous test until partial or total collapse occurred. Damage was cumulative for successive table motions.

A summary of the results is presented in Figure 7, where estimated peak ground acceleration (EPGA) is plotted against the damage index (DI). The EPGA is a more appropriate estimate of the relative table motions (ground motions) than simply using the peak ground acceleration (PGA). The damage index is a subjective measure of structural damage.

Damage was initiated in Model 1 during Test 4 (EPGA = 0.23g). Damage progressed during the next

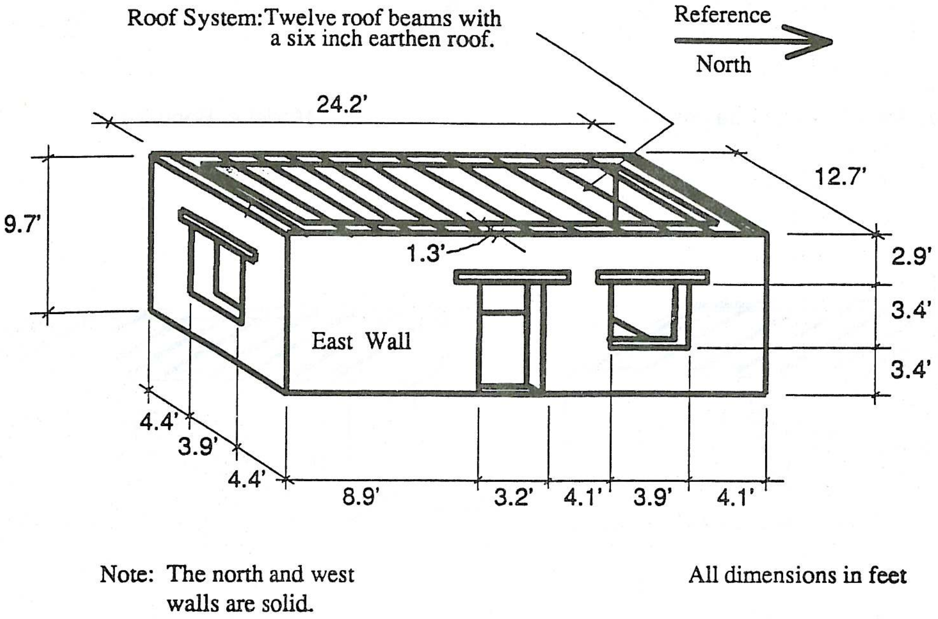
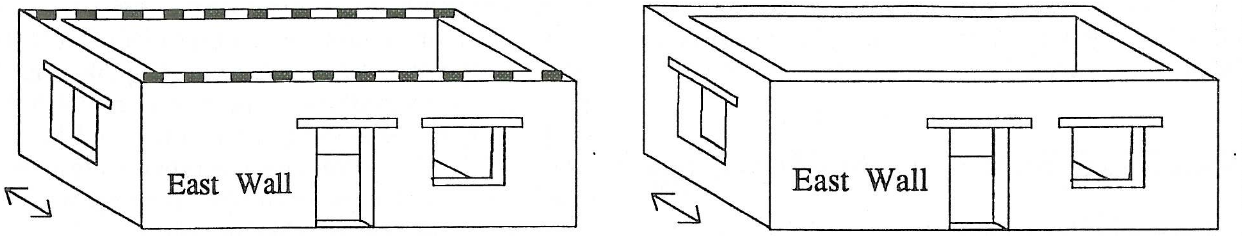
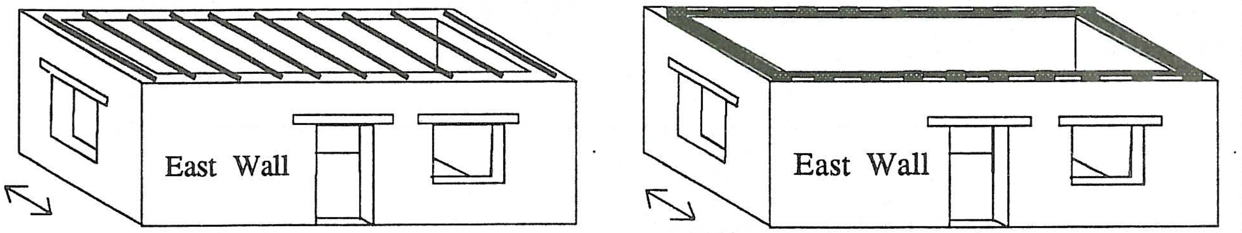


Figure 5. Drawing of prototype structure for 1:5 scale models tested at Stanford University.



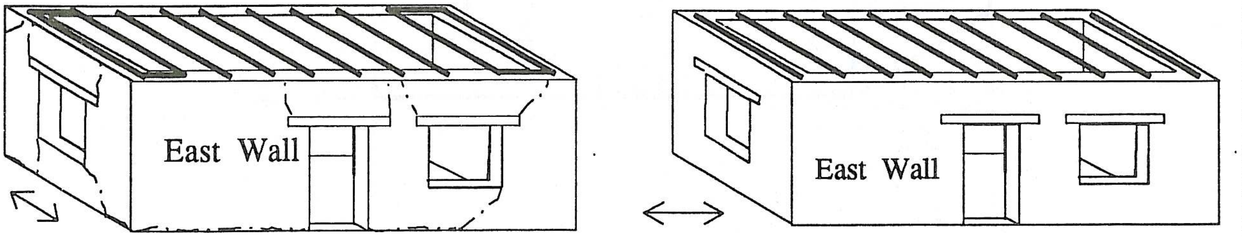
Model 1: "Base" Model

Model 2: Lightweight Roof



Model 3: Anchored Roof Beams

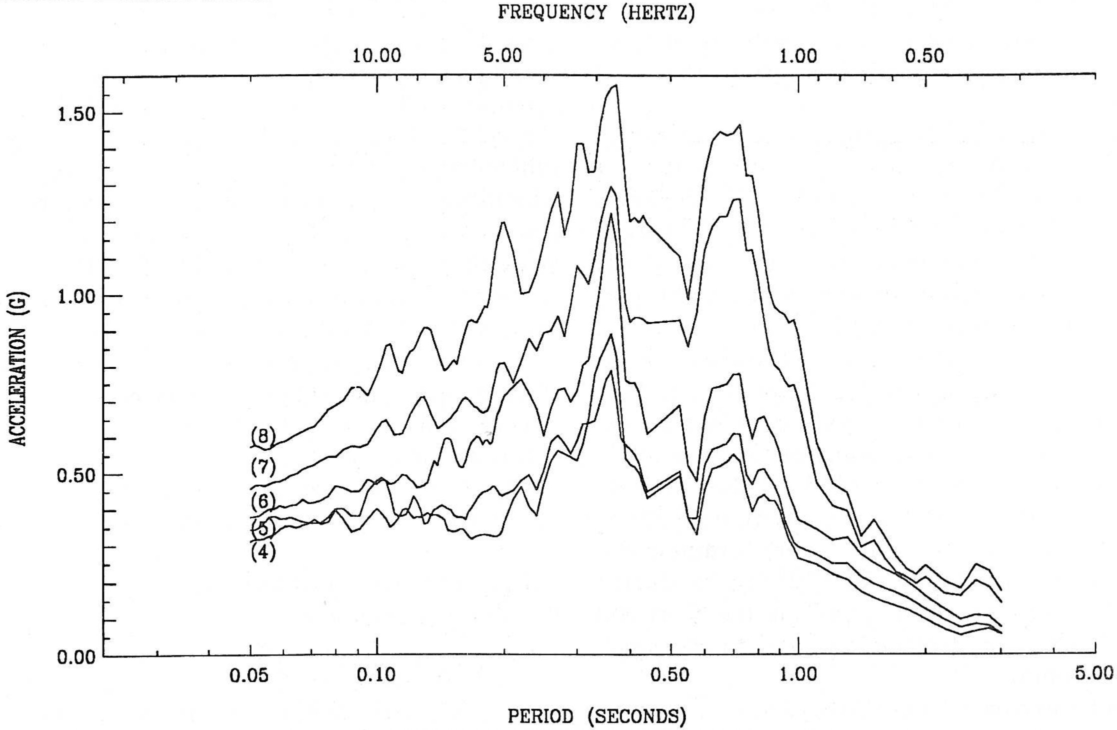
Model 4: Bond Beam



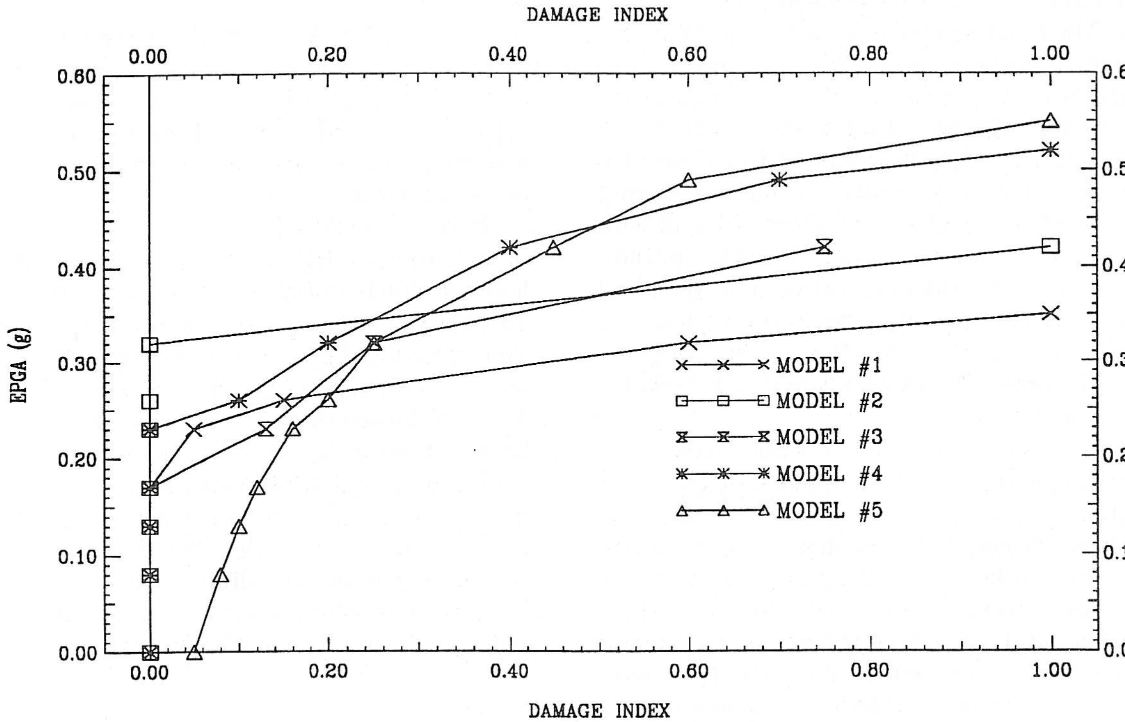
Model 5: Repaired Building with Beam Anchors and Ties

Model 6: Anchored Roof Beams

Figure 6. Schematic drawing of six 1:5 scale model buildings (arrows indicate direction of table motion).



a) RESPONSE SPECTRA FOR TESTS 4-8



b) EPGA VS. DAMAGE INDEX

Figure 7. Response spectra of Stanford shaking table tests and estimated peak ground acceleration (EPGA) vs. damage index.

two tests. The building nearly collapsed during Test 6 (0.34 g) and did collapse at the beginning of Test 7 (0.42 g) with the out-of-plane overturning of both of the long walls.

Model 2 had a lightweight roof and performed much better in the elastic range. No damage was observed during Test 6 (0.34 g), but cracks developed during Test 7 (0.42 g), and the long solid wall overturned and the long wall with openings nearly overturned. Although the change in the weight of the roofing system improved the elastic performance of the building significantly, it had little effect on the level of table motion at which collapse occurred.

The effectiveness of anchored bond beams was demonstrated by the performance of the long walls in Model 3; during the tests on Model 3, the anchored roof beams (even though there was no roof sheathing or a diaphragm) provided sufficient restraint to stabilize the long walls through Test 7 (0.42 g) but during that test the progression of cracks in the short end walls led to the out-of-plane failure of the short wall with the opening.

Model 4 had a wood bond beam that was attached to the long walls with anchor bolts that were grouted and anchored into the top two and a half to three courses. The bond beam had no effect on the elastic behavior of the structure but, as the building began to crack, the bond beam limited the deflection of the long walls and transferred the loads into the short end walls. Model 4 was the first building to survive Test 7 (0.42 g), and also remained standing during Test 8. During Test 8 (.54g), the short end wall with the opening was severely damaged and the portion of the wall over the lintel fell outward. If the bond beam had been anchored into the short wall, it would have improved the behavior of this wall by helping to constrain the broken block movement in both the in-plane and out-of-plane directions.

Model 5 showed the tremendous improvement in seismic performance that can be gained by the use of simple improvement measures. This model was accidentally damaged before testing and, subsequently, the cracks were patched, the roof beams were anchored and corner ties were added. To prevent the end wall collapse, small ties were added at the corners to connect the tops of the short and long walls. The performance of Model 5 was poor during the early stages of testing as the preexisting cracks opened. However, the building remained stable until the end of Test 9 (0.54 g). The improvement techniques used in this model specifically addressed the collapse mechanisms of the structure but had little effect on structural damage during small to moderate table motions.

The performance of Model 6 provides important information about the collapse potential of an adobe structure that runs contrary to common engineering opinion. In this test the motion of the shaking table was in the direction of the long walls, whereas the other tests were in the other direction. Typically, for a building with a plan similar to the prototype structure, it is assumed that the building is much more susceptible to collapse perpendicular to the long axis of the structure. But, simply by adding the minor improvements to Model 5, Model 6 became more resistant to collapse perpendicular to the long axis than collapse parallel to the long walls. Model 5 did not fail until the end of Test 9 (0.54g), whereas Model 6 was at the edge of collapse at the end of Test 7 (0.42g). Ties between the long walls and the roof beams were sufficient to stabilize these walls.

Some important conclusions based on the results of this testing program are:

1. Prior to crack development, the seismic response of the models was dominated by the high frequency characteristics of the input table motion.
2. Following initial crack development, the frequency characteristics of the buildings changed dramatically. The post-elastic response and collapse potential were dominated by the low-frequency, large displacement characteristics of the input table motion.
3. There is no clear relationship between the level of table motion that causes first cracking and the level at which collapse occurs; therefore, elastic analysis techniques are considered inappropriate for estimating the severity of ground motion that will cause structural collapse.
4. The collapse resistance of adobe buildings can be greatly improved by construction details that continue to hold the elements of the building together and that provide structural continuity after cracks have fully developed. During major seismic events, cracks will develop in adobe buildings but cracks should not be equated with failure of the structure.

Near Full-Scale Tests at UC Berkeley

The tests conducted at the University of California at Berkeley were performed on the shaking table in the Earthquake Simulator Laboratory located at the UC Richmond Field Station. A single 3/4 scale building was tested. The principal objective of the test program was to examine the benefits of two retrofit techniques: (a) a wood bond or tie beam and (b) external reinforcing or surface skin.

The test model measured 10 by 16 feet with a height of seven feet. The walls were 12 inches thick. A sketch of the structure is shown in Figure 8. The model was constructed directly on the 20 by 20 foot shaking table surface and oriented so that the longs walls were perpendicular to the direction of motion.

Roof beams spanned between the long walls, bearing on the top course of blocks. The roof beams were attached to the walls with one-inch diameter threaded rods, drilled and grouted into the top three courses. The model had no other reinforcement in the "base" model test phase.

The testing sequence had four phases:

Phase 1. "Base" structure without bond beam or reinforcement of any kind save anchorage of the roof beams to the walls.

Phase 2. Addition of a wood bond beam, which was bolted to the top of the walls using one-inch threaded rods. At the corner, the bond beam elements were lapped and connected using lag screws.

Phase 3. Addition of skin reinforcement to three walls (two long walls and one end wall). Reinforcement consisted of 2 by 4 inch 14-gauge welded wire mesh on one long and one end wall and 18-gauge stucco lath on the long wall. The mesh extended from the bottom course to the bond beam. The reinforcement was attached to both the inside and outside surfaces with pneumatically driven staples. All cracks from previous phases of testing were filled with adobe grout. No plaster or coating was applied over the skin reinforcement.

Phase 4. Skin reinforcement was applied to the fourth wall in the form of 2 by 4 inch welded wire fabric. Cracks from the previous phase were not repaired.

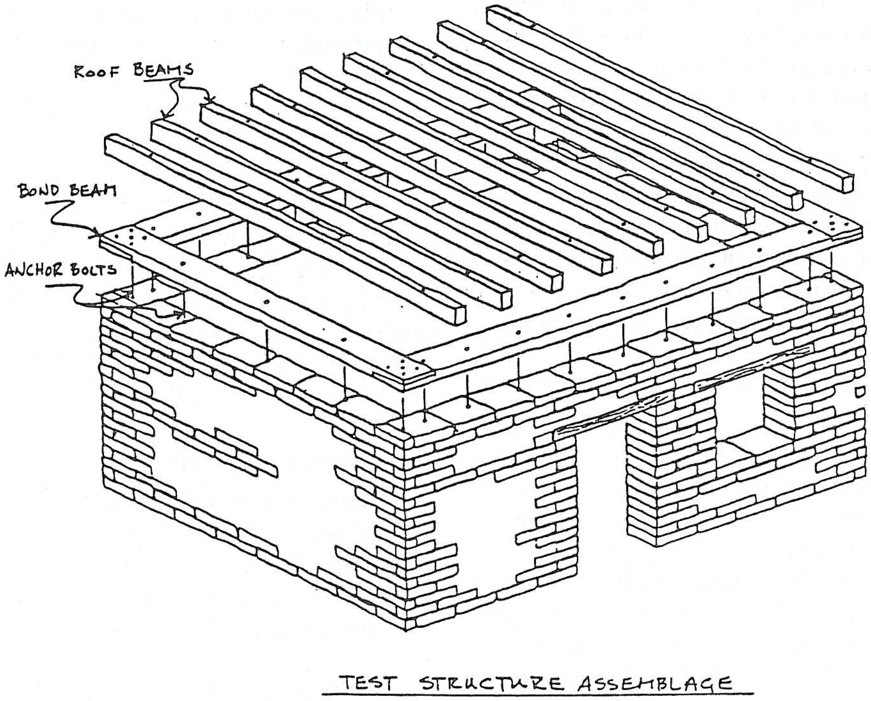


Figure 8. Drawing of 3:4 scale model tested at UC Berkeley.

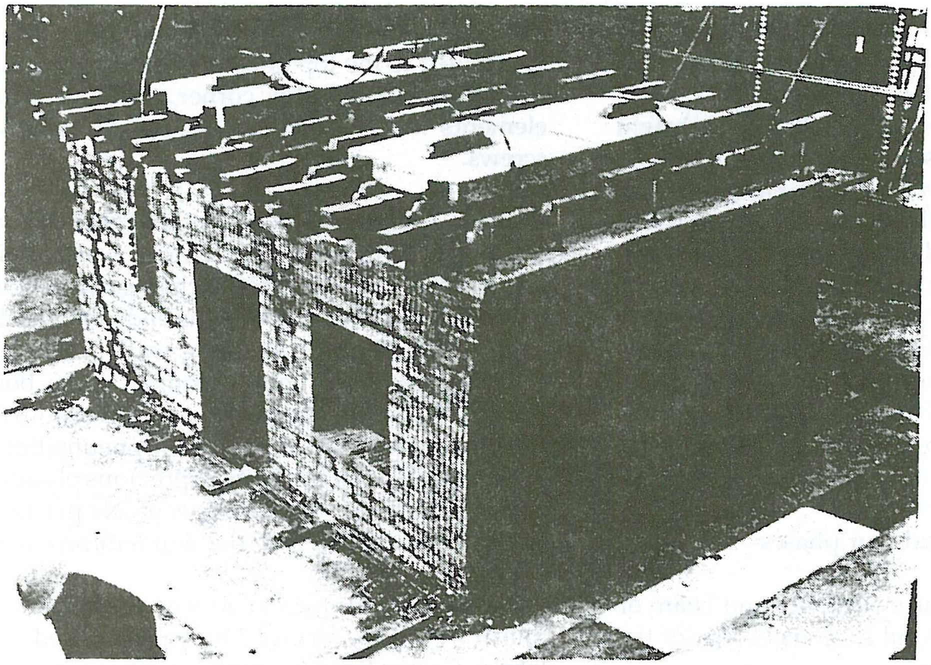


Figure 9. Photograph of damage to 3:4 scale model. Model was covered with wire mesh as part of Phase 4 of the testing sequence.

The shaking table motion was the Taft N21E record of the 1952 Kern County earthquake. The record was scaled for similitude requirements and filtered to overcome table displacement limitations. In some of the initial tests, the record was enriched in the 10 to 13 hertz range to initiate cracking, since this frequency range covered the undamaged natural frequency of the structure. During each testing phase, a sequence of test runs was made using the same record, gradually increasing the table motion severity until failure was incipient.

In Phase 1, the damage consisted of vertical cracks at three corners. The cracking was caused by out-of-plane motion of the long walls which resulted in excessive bending and tension reactions at these locations. A few vertical cracks were also noted above and around the door and window openings indicating out-of-plane bending failure of the front long wall.

In Phase 2, the damage consisted of in-plane diagonal cracking of one end wall. This was the result of the bond beam transmitting the out-of-plane reaction forces of the long walls into in-plane forces in the end walls. One end wall was severely cracked while the other end wall suffered no observable distress.

Repairs were made to the damaged walls before Phase 3 began. The damage in Phase 3 consisted of in-plane diagonal cracking of the unreinforced end wall similar to the other end wall in Phase 2. Repaired cracks in the reinforced end wall were reopened early in Phase 3 but remained narrow.

Welded wire fabric was attached to the fourth wall prior to Phase 4. With all four walls reinforced, the structure proved to be extremely tough, exhibiting considerable ductility under repeated runs of the table motion. In the last series of test runs, the model sustained five sequences of table motion, lasting a total of 60 seconds and each having maximum table displacements of ± 6 inches. At the conclusion of testing, the end walls were severely cracked and the reinforcing skin was broken and/or pulled free from the walls in places, but the model remained intact and the vertical load path was still capable of carrying the roof load (Figure 9).

The use of welded wire on the exterior was prompted by the seismic safety needs of typical residential adobes in Central and South America. It was viewed as a low-cost, owner implementable retrofit approach. It is not necessarily appropriate for historic adobes. The importance of this experiment to historic adobes is that the wire fabric substantially improved seismic performance by providing continuity across cracks and impeding block movement, while only providing nominal additional strength.

Observations from the Tests

It is difficult to make definite comparative conclusions from these tests because only a single building was tested at this scale. But combined with the observations from the reduced-scale tests performed at Stanford, some important observations can be made:

1. The strength of the wood bond beam was sufficient to transfer the loads from the out-of-plane walls into the short end walls, even though no roof diaphragm was present. From observations of the dynamic motion of the structure, the flexibility of the bond beam in the vertical direction allowed the bond beam to move with

the motions of the damaged adobe wall.

2. The use of welded wire mesh attached to the surface of the adobe (without the addition of a surface coating) provided sufficient restraint on the broken sections of the wall to prevent progressive failure from occurring.
3. The bond beam anchors functioned well throughout the testing program and did not cause local and progressive damage.

Strength-based and Stability-based Retrofitting

There are two approaches to improving the earthquake performance. *Strength-based* design refers to the process of focusing on the strength of material, the individual connection behavior and the overall structural configuration (such as the addition of shear walls or a diaphragm) and, therefore, the elastic behavior of the building. It focuses on traditional issues of delaying cracking, etc. *Stability-based* design focuses on the overall performance of the system and on allowing the post-yielding behavior to "induce" overall stability of the structure. It reduces the potential for heavy structural damage and collapse.

The conventional engineering approach to seismic retrofit is strength-based—that is, it provides sufficient strength for the structural elements to resist the forces generated by the elastic response of the building during a design level earthquake. It is understood that the forces generated during major seismic events will exceed those generated during the design level event. However, it is assumed that the nonlinear deformations of the material and connections have sufficient ductility to dissipate the additional energy from a larger earthquake.

The second approach—a stability-based approach—specifically addresses the post-elastic (post-damage) response of these buildings. This approach requires an understanding of the dynamic characteristics of a damaged adobe structure and application of techniques that prevent severe damage and/or collapse. This second approach specifically addresses the stability of the post-cracked building.

These two approaches are not mutually exclusive. The strength-based approach addresses the elastic behavior of the structure while the stability-based approach addresses the post-elastic performance. The two approaches are, in fact, complementary, or at least they can be. It is important to understand which aspects of the building performance each approach addresses and which aspects are not addressed.

The application of only a "strength-based" analysis is not sufficient to determine the performance of thick-walled adobe buildings. The use of only an elastic approach can be justified when there is a good relationship between the level at which first yield occurs and the level at which the structure collapses. In the case of thick-walled adobe construction, there is no clear relationship between these two events. In fact, some stability-based retrofitting measures may have absolutely no effect on the initiation or prevention of minor cracks but may have a tremendous impact on the development of severe damage and on the prevention of collapse.

The plot in Figure 10 is presented to represent graphically the progression of damage a collapse hazard adobe (e.g., one with thin walls and minimal roof and wall connections): one line (ABC) represents the building in its original condition; line DEF represents the damageability of the structure with a stability based retrofit; and, line GHI represents the damageability of the structure with a strength based retrofit. The horizontal axis is earthquake intensity which is merely a general term used to represent the severity of the earthquake ground motions. The vertical axis is the "damage index" (DI), which represents a qualitative assessment of structural damage ranging from non-damage to 100% damage. Figure 10 provides a graphic representation of the differences in damage

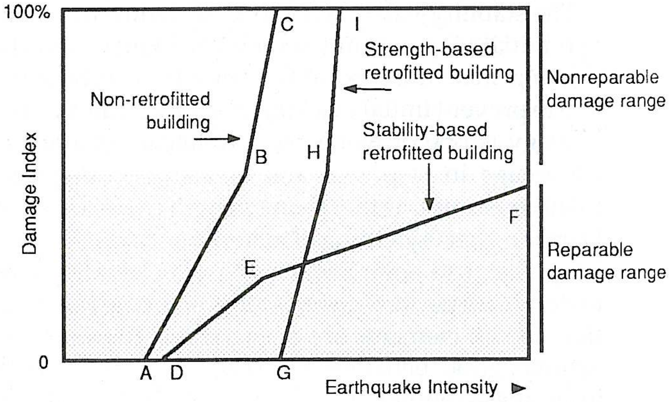


Figure 10. Variations of damage index with severity of earthquake intensity comparing the expected performance of existing, strengthened and retrofitted buildings.

behavior of a locally strength-based retrofitted building and that of a stability-based retrofitted building. These lines describes the ending states for adobes in different stages of damage for different earthquake intensities. Strictly speaking, these are not curves that describe the progression of damage to a structure as the intense of ground motion increases during an individual earthquake.

Under "normal conditions" an adobe is not damaged until a threshold earthquake intensity is exceeded—Point A. Damage then progresses quickly to point B for increasing increases , and then rapidly to collapse for small increments in the intensity, C. This line is typical of the behavior of brittle materials. However, many adobes have structural characteristics (e.g., thick walls) that cause them to behave less catastrophically.

A strength-based retrofit tends to displace the point of initial damage G to a somewhat higher intensity, after which, damage progresses until a critical point H above which damage is no longer repairable. Once the strengthened additions to individual elements and connections fail, they have little beneficial effect on the global performance of the structure. Above H, global behavior of the structure becomes dominant and collapse ensues for small increments in intensity—point I. For a thin-walled structure, blocks are free to move and are not constrained by other elements of the structure.

The stability-based retrofitted structure has damage initiated at a point somewhat higher than the existing structure—point D—since there is little desire to prevent initial cracking in such a strategy. The strategy is one of using the non-linear behavior to advantage in response, and focusing on displacement constraints rather than strength characteristics. Damage, that is yielding of material and connections, progresses to a point E where global behavior begins to dominate performance. At this point the stabilization retrofit elements are engaged and the structure exhibits good behavior, resisting collapse for high intensities—point F.

While strengthening yields distinctly better damage performance for lower intensities, stability-based retrofitting may be the only practical way to achieve life safety objectives of preventing collapse. Of course, as discussed above, a combination of these approaches may be very attractive, with strengthening approaches displacing the intensity at which damage initiates and retrofitting limiting heavy damage and preventing collapse.

This hypothetical example is meant to illustrate the potential difference in behavior between adobe buildings with different seismic retrofit measures. In the presentation of the following experimental data, similar comparative performances were observed in the reduced-scale models tested at Stanford University (refer to Models 1, 2 and 5).

Other interpretations of these lines are appropriate for different assumptions on the type of structure considered. For an adobe that has thick walls and substantial existing cracks, line DEF could represent its behavior. Such a building might have walls that have been effectively tied into the roof system and cabling that has been wrapped around the building at the roof line and attached to the roof system or other strategies that tie the overall system together. The cabling allows the movement of adjacent perpendicular walls while still maintaining overall structural continuity. Even in relatively minor earthquakes the existing cracks open but the building only suffers minor crack damage even in larger earthquakes. Only when the size of the earthquake approached the "maximum earthquake" expected at that site does the damage become severe; collapse is avoided under all circumstances.

Strength-Based Analysis

A strength-based analysis or design procedure uses analytical techniques in which the resistance of the structure is based upon the elastic strength of the material. The dynamic character of the earthquake ground motions are most often replaced by an equivalent static force. When using a strength-based approach, the design forces are always substantially less (by a factor of 5 to 10) than the forces that may be expected in larger seismic events at a specific site. The assumption of this approach is that the ductility of the materials and connections will be sufficient to withstand the demand of these larger seismic events. Conventional strength design usually only assesses the possible consequences of extreme deformations by assessing the elastic deformations under larger-than-design loads.

Strength-based engineering assumptions would not indicate that adobe buildings can perform well during even moderate seismic ground motions. Historic adobe buildings have massive walls and the adobe itself is a low-strength material. The massive walls mean that the dynamic, or equivalent static, forces applied to the structure are large. The low strength property of the material means the that the tensile capacity of the material is easily exceeded. Both of these factors make the design of acceptably performing adobe retrofits difficult using a strength-based approach.

Thin-walled masonry construction can fail catastrophically simply due to gravity conditions shortly after the material is cracked through the section and blocks have formed. But thick-walled adobe construction is observed to be capable of sustaining deflections well beyond the elastic limit of the material. The stability of such walls may not be threatened even when the wall deflections are as much as 100 times the deflection at the elastic limit of the adobe material.

The "structural ductility" of a building system (not material ductility) is a critically important characteristic of the seismic design of a building. Thick-walled adobe buildings can exhibit substantial structural ductility even though the building's construction material, adobe, itself is brittle. Structural ductility is defined as the capacity of a building to deform beyond the deflections at the elastic limit of the material while the building still maintains its load-carrying capacity. The structural ductility of an adobe building is proportional to the thickness of the walls.

Stability-Based Analysis

An approach that is based upon an understanding of the post-elastic behavior of adobe buildings explicitly addresses the stability of a structure. If only a strength-based approach is used, the stability of an adobe structure is implicitly and, perhaps inaccurately, anticipated.

A stability-based analysis can take advantage of the unique characteristics of adobe construction's post-elastic behavior. The walls must be relatively thick, as they are in the vast majority of existing historic adobes, to exhibit the ductile performance characteristics required to sustain the forces of large earthquakes. Adobe masonry cracks at a relatively low level of seismic excitation due to the low strength of the material, but the cracks typically form along mortar joints perpendicular to the plane of the wall. This makes unlikely the slumping of material under gravity loads.

It is often assumed that an unreinforced masonry structure (such as adobe and brick) is only safe while it is largely undamaged, that is, without substantial cracking. Once cracks have developed, the usual analysis proceeds to note that the material has lost its continuity and strength and, therefore, the building is unsafe because the damage means the building is at the point of imminent collapse. From the discussion of the experiments above, it should be clear that a thick-walled adobe building it *NOT* unstable after cracks have fully developed. A thick-walled adobe building still retains considerable stability characteristics even in a fully cracked state.

The extent of retrofit intervention required to stabilize a historic adobe is often relatively small compared to that required by conventional strength-based design. A stability-based approach relies on many of the inherent properties of historic adobe construction. The following are primary considerations of a stability-based design approach:

1. Allow out-of-plane rocking. Out-of-plane stability of thick adobe walls is not as serious a consideration as generally assumed by conventional, strength-based methods.

2. Provide restraint at the tops of walls. Additional restraint at the tops of thick adobe walls will greatly increase the out-of-plane stability of broken blocks.

3. Provide flexible connections between perpendicular walls that will tie the walls together. Perpendicular walls have very different deflection characteristics, so flexible connections are important.

4. Provide ties that resist the relative and permanent displacement of adjacent, cracked blocks. Very little force is required to greatly reduced both in-plane and out-of-plane block movements during extended seismic excitation.

The fundamental advantage to a stability-based approach is that it takes advantage of the inherent characteristics of historic adobe construction. A stability-based intervention can greatly reduce the risk of severe damage and/or collapse of a building while, at the same time, protect lives with a relatively low level of intervention.

Review of recent retrofit designs

The development of a new approach to retrofitting can benefit substantially from experience of designers who have retrofitted adobes. The GSAP project has completed a preliminary examination of the engineering decisions and details of design and analysis used in the seismic rehabilitation of historic adobe structures in California. This evaluation first identified several engineers and architects in California who have been involved in seismic rehabilitation projects on historic adobes.

Eight representative structures, retrofitted over the past 15 years, were selected for review (Table 1). These structures represent a variety of building types and approaches to retrofit design. This group is not meant to be complete, but to be representative of the approaches that have been taken and to illustrate the types of problems likely to be encountered. Meetings were held with the architects and engineers involved to obtain pertinent information and to discuss the specific engineering decisions and constraints they faced. As GSAP progresses many more structures will be assessed.

The Uniform Building Code (UBC) was often used to provide guidance in adobe retrofit design prior to the development of the *California State Historical Building Code (SHBC)*. Unfortunately, the *UBC* lacks specifications for existing unreinforced adobe structures in Zones 3 and 4, as it does for most existing buildings. As a result, designers often allowed little or no strength for the adobe material and the solutions tended to emphasize the design of independent structural systems to carry the roof and floor loads and to provide supplemental support for the adobe walls. Essentially the adobe was thought to have no seismic capacity and required additional support to prevent its failure. The intent of the GSAP assessment of recent retrofits was to include a range of solutions and a time span that encompassed a significant change in adobe seismic retrofit philosophy.

Adobes were only one of several historic building types that were not accommodated in the *UBC*. With this in mind, the California Legislature authorized the *SHBC* on January 1, 1976. The first codified regulations were published in 1979; however, these regulations did not become mandatory until July 1, 1985. The current edition of the *SHBC* explicitly recognizes the inherent strength of historic adobe and allows:

1. Engineering judgment in the evaluation of strength and performance based on historical evidence.
2. Use of a maximum height-to-thickness ratio of 6 for single-story structures in lieu of a more complete out-of-plane evaluation.

Table 1 Characteristics of eight retrofitted historic adobes reviewed to assist in understanding the types of technical problems encountered in seismic retrofitting.

Building	Type of Retrofit
1 Cooper-Molera	Independent moment frame, grade beams
2 Casa Primera	Partial plywood diaphragm, steel straps and anchors
3 Reyes Adobe	Concrete bond bea, plywood diaphragm, earth anchors through bolts
4 Sepulveda Adobe	Concrete bond beam and corner columns, grade beams, steel rod cross ties at bond beam level
5 Roberto Adobe	Concrete bond beam, plywood diaphragm, earth anchors
6 Mission San Juan Batista	Concrete bond beam, plywood diaphragm, earth anchors
7 Pio Pico Adobe	Steel Straps and fiberglass earth anchors
8 Parra Adobe	Indeoendent timber frame with steel tie rods

3. A maximum allowable adobe masonry shear strength of four pounds per square inch (psi).
4. Inclusion of a reinforced bond beam at the second floor and roof levels.

The *SHBC* has had a dramatic effect on the philosophy of seismic rehabilitation of historic adobes. The following two examples illustrate the extreme difference in the philosophies before and after the SHBC.

Cooper-Molera Adobe, Monterey, California

The Cooper-Molera adobe (Figure 11) is actually a complex of historic adobe and wood-framed structures in Monterey, California. The two-story Cooper house was constructed in 1850 as an add-on and remodel of the east end of the existing Diaz Adobe. In addition, the Diaz Adobe was extended further west into what is now known as the Store, located at the corner of Munras Avenue and Polk Street (Forell/Elsesser 1977).

The foundation of the adobe is dressed chalk stone, and at the time of the seismic rehabilitation of 1977, it showed no signs of settlement. No significant cracks were found in the walls or the unbonded joints between buildings. Based on these observations, the retrofit engineer concluded that the adobe walls had not sustained significant seismic damage since its construction, even from the San Francisco earthquake of 1906 (Forell and Nordenson 1980).

Laboratory tests were conducted on 23 adobe samples found on site. The results of the tests were: (a) average compressive strength of 400 psi; (b) average flexural strength of 39 psi; and (c) computed shear strength of 20 psi (Testing Engineers 1977).

The seismic design criteria to be used was a problem from the outset. The National Trust for Historic Preservation (NTHP) is the owner of the buildings and the California Department of Parks and Recreation (DPR) is the tenant and operator. The NTHP

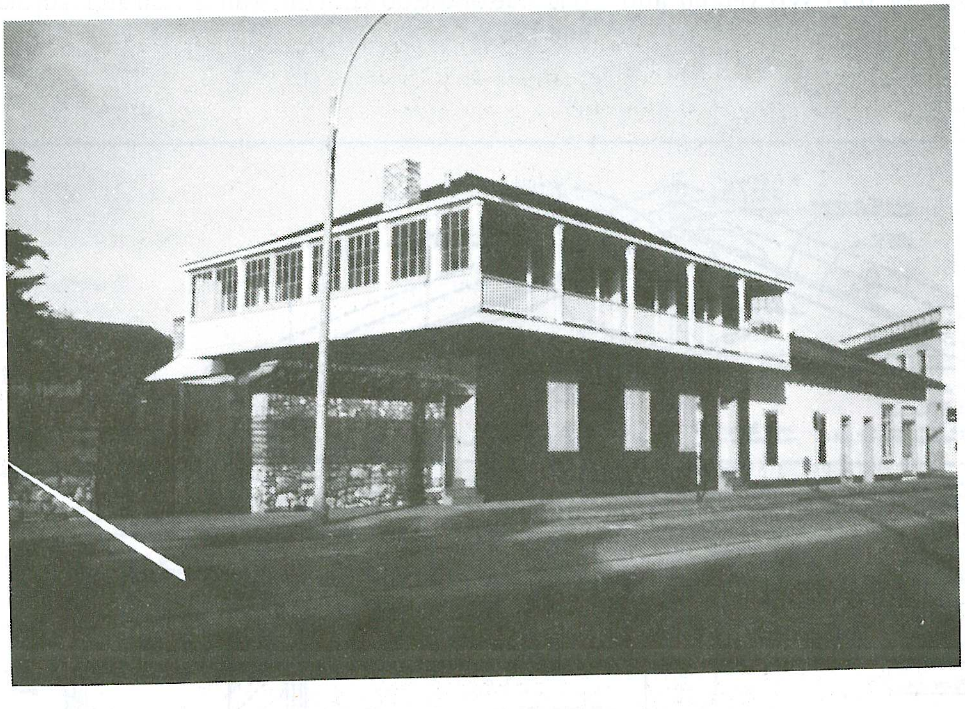


Figure 11. Photograph of the Cooper-Molera adobe.

was primarily concerned with the preservation of historic aspects of the building (i.e., the wall surfaces), whereas the DPR was more concerned with life safety. At the time, the SHBC had not been written and the main resource for evaluating and designing for life safety was the UBC. It was felt, however, that strict compliance with the UBC would have an impact on the building's historic fabric that was unacceptable.

Although the seismic retrofit design for the Cooper-Molera adobe was based on the 1976 UBC, it allowed the adobe walls to carry both their own gravity and lateral loads. Nonetheless, the engineer thought it prudent that the roof and second floor be independently supported in the event of wall collapse. Therefore, the design was based on the *UBC* 1976 Seismic Zone 3 requirements, with a K-factor equal to 1 for a dual lateral force resisting system. The design base shear was 0.105W, which was used to both analyze the adobe walls in-plane and to design the independent support of the roof and second floor. The walls were also evaluated for out-of plane bending using a lateral force of 0.15 Wp (Forell and Nordenson 1980).

The seismic retrofit measures adopted for the Cooper-Molera complex included:

1. Adobe walls allowed to carry their own vertical and lateral loads, both in-plane and out-of-plane.

2. Horizontal bracing for adobe walls provided by plywood diaphragms and structural steel tie beams or chords keyed into the walls.

3. Independent vertical and lateral support of roof and second floor loads by a system of moment frames and grade beams. A steel frame was selected for the Cooper and Diaz houses in an attempt to save the historic second-floor and roof framing (Figure 12). A concrete frame was used in the Spear warehouse because there was no need to preserve the roof framing and it was felt that the wall surface was not an important aspect to preserve.

The frames were chased into the walls and covered up. Depending on the relative importance of the particular wall surface, the chases were either cut into one side or the other of the wall (Forell and Nordenson 1980).

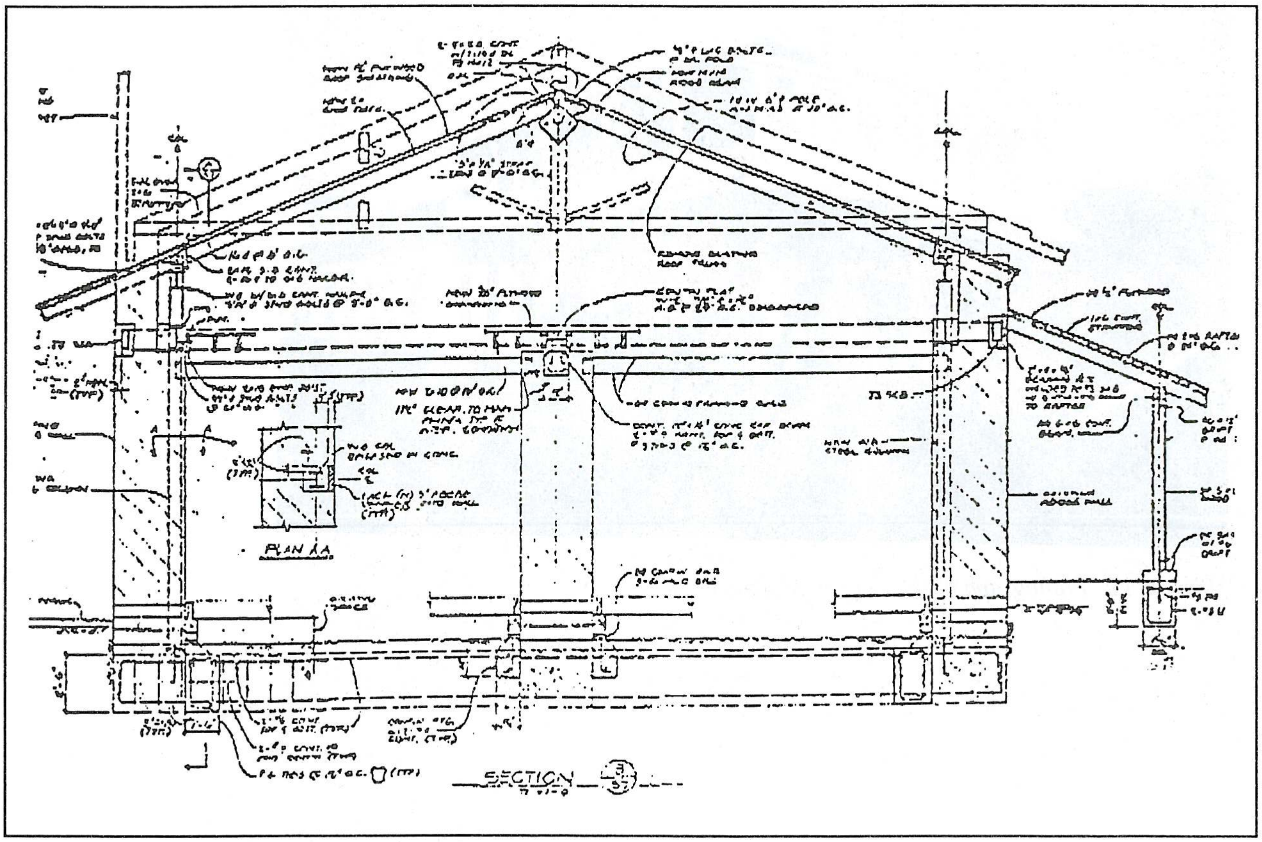


Figure 12. Section through Cooper-Molera adobe.

On October 17, 1989 the magnitude 7.1 Loma Prieta earthquake occurred in the Santa Cruz mountains near the San Andreas fault. The felt intensity in Monterey, about 28 miles south of the epicenter, was MMI IV. The peak ground acceleration recorded nearby at City Hall was only 0.07g. No damage to any URM buildings was reported in the vicinity of the Cooper-Molera adobe; this includes the historic adobes (*Earthquake Spectra* 1990). The Loma Prieta earthquake provided the most severe ground motion experienced by the retrofitted adobe to date, but should not be considered a test of these seismic retrofit measures, since the ground motions were not strong enough to exercise the retrofit measures.

La Casa Primera

La Casa Primera (Figure 13) is a single-story historic adobe located in Pomona, California. It was built in 1837 and was the first adobe in the Pomona Valley (Scawthorn and Becker 1986). The original building plan was approximately 30 by 55 feet. Exterior walls are 11 feet high and 26 inches thick (slenderness ratio 5). Interior walls are approximately 14 inches thick. The foundation is adobe block.

The adobe walls at the time of the rehabilitation in 1985 showed signs of localized foundation settlement with resulting cracks. Providing stability for the walls was the main concern during the rehabilitation activities (Donaldson 1991). The *SHBC* had just become a mandatory design document for this building and through it adobe was recognized as a structural (although archaic) material with strength and the capability to resist lateral force. The engineer and architect decided to reject the construction of a concrete bond beam at the top of the walls due to concern for the stability of walls during the rehabilitation process. It was felt that the construction of a concrete bond beam would have caused loss of lateral wall support by the existing roof framing. The engineer's interpretation of Section 8-904 was that it required a concrete bond beam only for erection or re-erection of walls, and that this particular retrofit involved neither (Krakower 1985).

The seismic retrofit measures used were a ceiling level plywood tie beam nailed to the existing ceiling sheathing and anchored to the perimeter adobe walls with Hilti Adhesive Anchors and steel straps (Figure 14).

The seismic evaluation of La Casa Primera was based on the ABK methodology (1986) for unrein-

Figure 13. Photograph of La Casa Primera.

forced brick masonry buildings. The plywood tie beam design was based on displacement control considerations outlined in that methodology. Anchor bolts were sized using the allowable shear values from the *UBC* Table 24-I and increasing them for ultimate load conditions in accordance with the ABK methodology. Bolt tests performed subsequent to this project have confirmed that such allowable shear values are indeed appropriate.

The evaluation of out-of-plane wall stresses was based on the height-to-thickness ratios specified in the *SHBC*. In-plane shear stresses were based on the

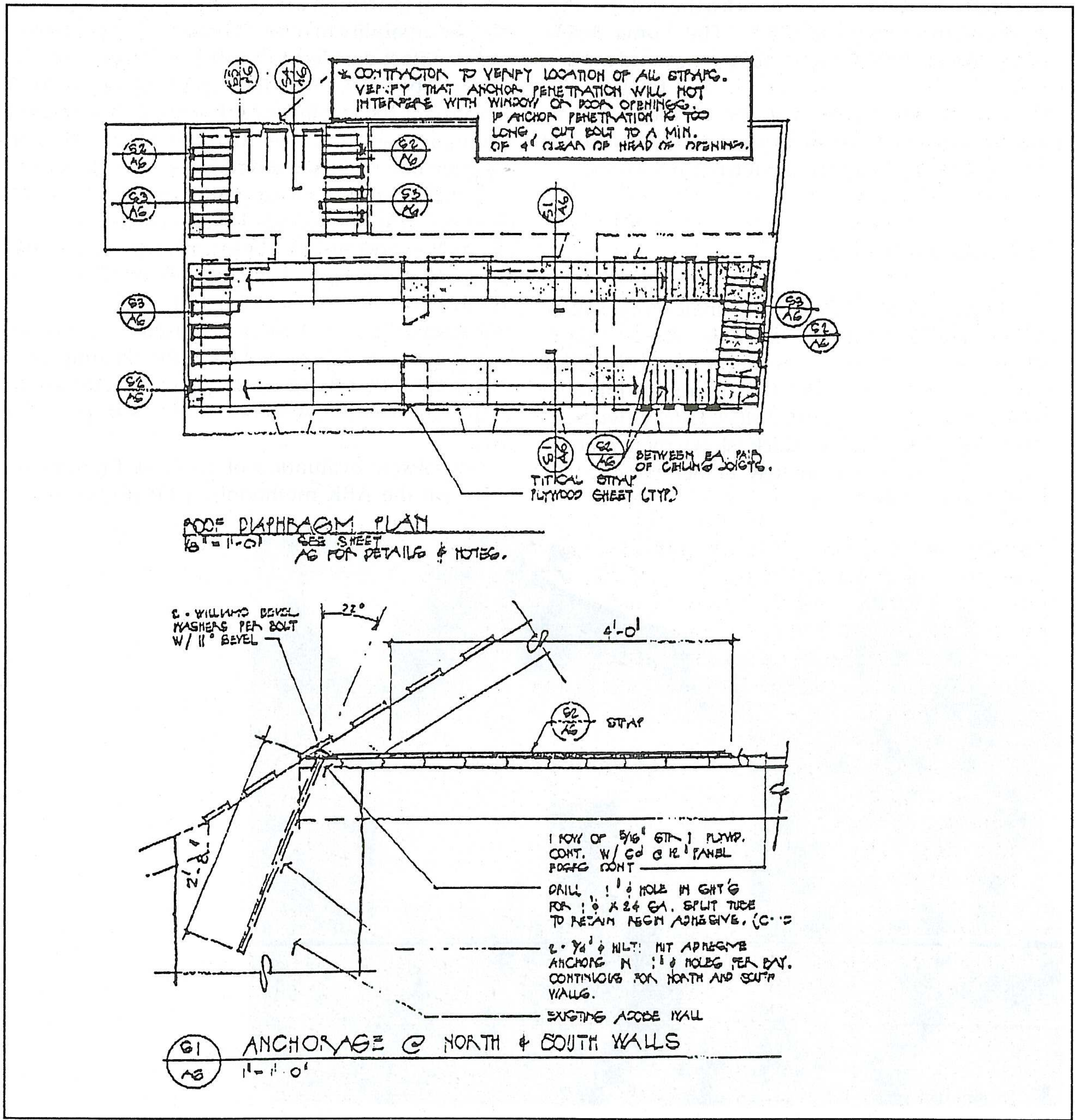


Figure 14. *Plan and detail La Casa Primera retrofit.*

tributary weight and a lateral force factor of 0.4. Maximum adobe wall shear stress due to the design lateral force was determined to be 1.7 psi.

On February 28, 1990, a magnitude 5.5 earthquake struck the Upland, California and surrounding areas. It was centered three miles northwest of Upland, near the San Gabriel mountains. While the intensity of strong shaking was modest and the duration of shaking short, there were reports of damage in the nearby Pomona area including (EERI 1990):

1. Damage to many older downtown buildings
2. Severe damage to City Hall
3. A fallen church steeple
4. Many fallen chimneys
5. Ruptured waterlines near Pomona Valley Hospital

The performance of La Casa Primera was good. Damage was confined to minor diagonal and vertical wall cracking. Most of these cracks appear to have existed prior to the seismic rehabilitation. The wall anchors and plywood tie beam were inspected in the attic area, but revealed no damage to or moving of these elements.

A "sister" adobe, about 300 yards away had not been retrofitted, but was observed to have similar types of wall cracks. The chimneys of the "sister" adobe did fail. It appeared that the only difference in performance was that the chimneys of La Casa Primera, which had been seismically strengthened. It was concluded that the retrofit measures were not significantly tested during the Upland earthquake.

The following conclusions have been reached on recent retrofitting designs:

1. The SHBC has changed the philosophy of design decisions for seismic retrofits of historic adobes. The philosophy appears to have changed from more to less intervention to achieve seismic rehabilitation.

2. Interpretation of the SHBC may allow other types of bond or tie beams (e.g., plywood, steel angles, etc.). Indeed, the next version of the SHBC may explicitly allow other, equivalent, types of tie beams.

3. Anchorage of bond beams and/or diaphragms to walls with anchor bolts or rods has been used extensively as a seismic retrofit method. There is a wide range of thought, however, on the proper size, spacing, and embedment depths for such anchors.

Because of the strong influence that the SHBC has had on design decisions for recently retrofitted historic adobes, it is worth pointing out some of the problems associated with its use, including:

- Although the SHBC recognizes adobe as a unique building material with strength properties, it is not based on a consistent understanding of how these types of buildings behave in seismic events.
- For exterior bearing walls, the height-to-thickness ratio requirement is either "6 or 5 for the most hazardous earthquake zone" (State Historical Building Code 1985). It is not clear which it is, six or five. There are also no ratio requirements for exterior non-bearing walls nor for interior bearing and non-bearing walls.
- The height-to-thickness ratio requirements for the first floor of a one and one-half or two-story structure are unclear. It makes little sense to require the overall wall height-to-thickness ratio to be 6 or 5 in this case. This would mean that the walls of two-story adobes would have to be unusually thick to meet the requirement.
- It is unclear when a bond beam is required for seismic rehabilitation. The SHBC states that a bond beam is required for "erected or re-erected" unburned clay masonry. Most retrofitted historic adobes do not require the erection or re-erection of walls. Is a bond beam required under these circumstances?
- Materials testing for strength appears to be required for adobes, but is not often done. It is unclear whether the allowable shear stress for analysis purposes is meant to be affected by the outcome of such tests.

Seismic Retrofit Issues for Historic Adobes

Understanding the Implications of Design Approach Selection

The retrofit design approach for historic adobe buildings is based on assumptions about building behavior. When a strength-based design approach is used exclusively, it is assumed that the elastic behavior of the building is primary and that post-elastic behavior is similar to the elastic behavior and its effects on the structure are secondary. At best, a strength-based design method is valid up to the point that the building cracks and may be used to limit minor cracking during small and moderate earthquakes. The preexistence of cracks in historic buildings may invalidate the basic assumption of an undamaged building and, therefore, the use of analytical methods based on elastic behavior would be inappropriate.

The earthquake performance of a structure is governed by many factors. The magnitude and seismic characteristics of the earthquake, the propagation path to the site, and the geotechnical characteristics of the site are clearly important. However, they are not under the control of the designer except through the selection of the design loads to be accommodated.

The characteristics of the structure itself that dominate the seismic response include its: configuration, continuity, redundancy, compatibility, energy absorption capacity and strength. And of course, the physical condition of the structure strongly affects its seismic performance. These issues are addressed below and a seismic typology for historic adobe buildings is presented.

Configuration Issues

The configuration characteristics of historic adobe buildings that are of principal importance in understanding their seismic performance are the following:

Building plan. The overall layout and the number and location of internal cross walls will affect building performance. Unsupported length of walls will affect the performance of those walls at least up to the point that the walls crack. Due to the low strength of the adobe material, when the span between cross walls is greater that 1.5 to 2.0 times the height of the wall, the internal cross walls will have little effect on the out-of-plane stability of the exterior walls. Internal cross walls can help to improve the stability of exterior walls but can also be a source of cracks. Building plans that are L-shaped or U-shaped present additional opportunities for perpendicular wall intersections.

Wall dimensions. Of principal importance in the performance of historic adobe buildings is the thickness of the walls. Not only is the height-to-thickness ratio important but also the absolute thickness of the walls. The greater the absolute thickness of the wall, even with the same slenderness ratio, the more resistant is that wall to seismic damage. The height of a wall is defined as the floor to floor height when the floor, ceiling or roof framing is connected to or rests on top of the wall. The majority of the existing historic adobes in California, many of which have withstood major earthquakes, have thick walls with height-to-thickness ratios of 5 or less.

Number of stories. Two-story adobes have substantially different problems and performance characteristics than those with only one-story. The overall wall height is higher but, ordinarily, the first floor wall thickness is greater than that of the second floor. The dynamics of a two-story system are clearly more complicated than a single-story building but the same principals of design apply to each type of building. The proper connection and bearing between the second floor joists and the both the bearing and non-bearing walls is of particular concern.

Roof system and roof-to-wall connections. The connections between the roof and the walls are particularly important because of the stabilizing effect the roof system can have on supporting the tops of the walls. The importance of connections between all structural elements (ceiling beams, balconies, etc.) is also important in that any individual element can slide out and collapse if the attachment or bearing is not adequate.

Openings. The size and number of openings (doors, windows, etc.) can be very important because they often define the location that cracking begins and, therefore, when damage fully develops they determine much of the overall crack pattern. In many of the Mission churches, the openings are only a small percentage of the overall wall space but, even then, the openings in the end walls are often a source for crack propagation.

Seismic Typologies of Historic Adobes

The GSAP study team reviewed the important characteristics of a number of historic adobe buildings during a series of field visits to 23 sites (Table 2). The focus of the reviews was on those characteristics that affect the seismic performance of the buildings studied.

Categories for historic adobes are indicated below to provide general building typologies for understanding building behavior during earthquakes. The categories were defined on the basis of the similarity of expected global response of a particular structure. Given the large variety of historic adobe construction, it may be possible to create categories too numerous to be useful. To reduce the number of structural groups, three principal characteristics were used:

Table 2. Historic adobes site visited during the GSAP field investigations.

Soberanes Adobe
Stevenson House
Mission San Miguel
Plaza Hall
Mission San Juan Bautista
Cooper-Molera Adobe
Santa Cruz Mission Adobe
Martinez Adobe
Rancho Los Alamitos
Mission San Gabriel Convento
Andres Pico Adobe
Lopez Adobe
Larkin House
Pacific House
Mission San Antonio
Castro-Breen Adobe, San Juan Bautista
Casa Amesti
Bolcoff Adobe
Castro Adobe, Watsonville
Rancho Los Cerritos
Pio Pico Mansion
Serra Chapel Mission San Juan Capistrano
Mission San Fernando

1. Wall thickness and height-to-thickness (slenderness) ratios
2. Number of stories
3. Interior cross walls

The use of these general characteristics then allowed the grouping of buildings into two basic types and four total categories. The first subdivision is based primarily on wall thickness. The larger mission buildings such as church buildings and conventos generally have wall thicknesses between four and six feet. This separates those buildings from the second basic type of residential and commercial structures (one and two story buildings) where typical wall thicknesses range from a foot and a half feet to three feet.

Thick-Walled Mission Buildings

Church buildings: The large assembly hall used for the main church buildings is a distinctive building type. The walls are very thick (four to six feet) and the plan of the building is typically a single open area. The height-to-thickness ratio of the building walls is usually about 5. The width of the building is typically 30 to 40 feet and the length can be well over 100 feet. Because of the length of the building and the absence of cross walls, this type of assembly hall creates particular problems when approached with conventional design methodologies that analyze only the elastic, undamaged behavior of the building. Conventional methodologies may also be inappropriate due to often extensive existing cracks.

Conventos: Conventos are also thick walled buildings (from three to four feet) but the interior spaces are usually separated into a number of smaller rooms by other massive adobe walls. If a convento building has walls that are thinner than three feet, the building should probably be placed into one of the last two categories. The two important characteristics of convento buildings are: (1) the thick walls; and (2) regular internal cross walls.

The cross walls accomplish functions that are, to some degree, contradictory. Cross walls can benefit the structural performance by acting as stiffening elements for the long walls of the structure. However, cross walls can also create local areas stress concentration and local cracking. By creating regular cracking zones, the walls may be broken up into a variety of smaller sections, each of which needs to be considered and supported during severe ground motions.

Nevertheless, because of the massive walls of many convento buildings, this type of problem may not be of great significance. Very thick walls, especially with intermediate floors, greatly reduces wall rocking. Thick-walled conventos at Mission San Fernando, Mission San Juan Bautista and Mission San Jose have all survived large earthquakes with limited damage. It is possible that such walls are per se seismically resistant, and that little or no intervention is necessary.

Residential and Commercial Buildings

Single Story Buildings: The small, single-story adobe is the simplest of the building typologies. Although these buildings may or may not have interior cross walls, their expected performance is probably dominated by the height-to-thickness ratios of the exterior walls. A greater stability is expected if the ratio is closer to 3-4 than to 6-7.

Two-Story Buildings: The two-story adobe building is a classic type of construction in many parts of California. The buildings often have thick walls on the first floor that are reduced in thickness on the second floor. Gabled roof systems often have high adobe gabled ends. Balconies often exist at the second floor level and can be cantilevered or supported by exterior posts. Each of these conditions is likely to

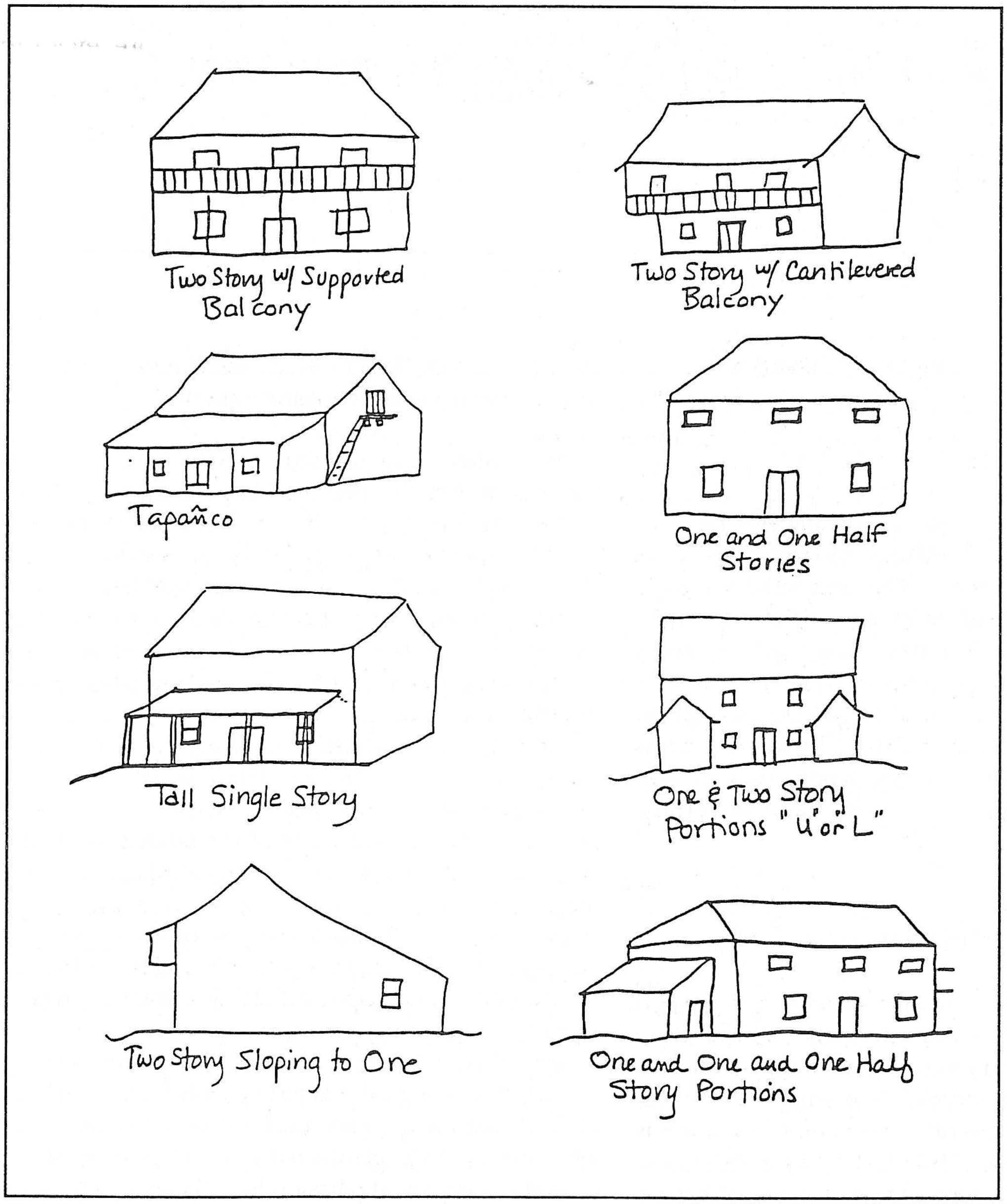


Figure 15. Typical architectural typologies of California adobes.

affect the seismic performance of the building.

Other Variations

Some of the are numerous variations of architectural building configurations are shown in Figure 15. These variations can be considered as special cases of the four previously listed building types. For example, a tapanco building is a special case of a simple single-story building, whereas, a building that has one and one-half stories is probably closer to a two story building. Some two-story buildings have attached single-story adobe additions that create L-shaped or U-shaped buildings. Damage may occur at the contact, but it is likely to be similar to that of any two perpendicular walls.

Effects of Existing Conditions

Moisture: The moisture content of adobe is a critically important factor that determines the mechanical performance of adobe walls under earthquake or other static or dynamic loading conditions. Moisture can get into the adobe through moisture penetration from wind driven rain, from roof leaks, or from capillary action (water transmitted through the soil to the foundation, which can be from landscape irrigation or snow accumulation). The strength of adobe decreases dramatically when the blocks are wet. Moisture has a serious effect on the seismic performance of the building.

Adobe may also lose its strength as a result of repeated wet/dry cycles. Although drying of wet adobe will improve its mechanical properties, adobes damaged by wet/dry cycles may never recover their original strength.

The effect of wet/dry cycles on adobe has not been studied extensively. Tests at the Getty Conservation Institute involving wetting and drying of newly formed adobe blocks have shown that the surface property deterioration observed in the case of naturally weathered adobe can be duplicated artificially. The effects of alternate increase and decrease of relative humidity on the material character of new adobe has been observed in situ with an environmental scanning electron microscope. Hydration and dehydration of expanding type clays in the adobe results in clay particle size reduction and physical movement of clay particles, both of which can lead to disintegration and weakening of the adobe.

Although adobe mortar is often made from the same material as that used for the bricks, mortar and brick appear to weather at different rates and structural discontinuities are observed frequently at mortar-brick interfaces. Weathering rates for brick may be greater or less than those for mortar, depending on adobe composition, construction procedures, and local weathering conditions. These discontinuities could have a considerable effect on the seismic performance of adobe walls.

Existing damage: A knowledge of the presence and location of existing damage is important for accurately assessing seismic vulnerability. Existing damage may become progressively more severe during additional seismic shaking.

Structural Issues in Stability-Based Retrofitting

The fundamental elements of a stability-based retrofitting prevent the most frequently occurring failure modes and provide structural continuity that prevents progressive structural failure. Typical damage to adobe structures during an earthquake can be classified as one of the following:

1 out-of-plane overturning of walls
2 in-plane shear cracking
3 separation of adjoining walls and
4 roof collapse which may result from a combination of the other three types of failure.

Other issues that should be addressed in a complete retrofit design strategy include diaphragms, connections, compatibility and structural redundancy.

Out-of-plane wall motion: The likelihood of out-of-plane collapse of walls, termed overturning, is less than predicted by conventional strength-based analytic procedures. Out-of-plane failure is expected in buildings with thin walls and high height-to-thickness ratios, where the initiation of cracks through the wall section does, in fact, threaten the stability of the wall. Although the threat of out-of-plane failure for thick-walled adobe structures is less than a conventional analysis predicts, the possible consequences of such a failure make it very important to deal with this hazard in a thorough and consistent manner. Out-of-plane wall failures are a common mode of failure that have particularly significant effects on preservation of the structure and on life-safety.

The out-of-plane rocking motion of a thick adobe wall can be very large compared to the elastic deformations. Gravity forces help to stabilize the walls and additional tributary vertical loads may add to that stability. The stability of free-standing walls with slenderness ratios less that 5 is substantial. This seems to be confirmed by the number of such walls that have withstood repeated strong motion earthquakes, as well as demonstrated in many laboratory tests.

The provision of restraints at the tops of walls can provide significant additional out-of-plane stability and adds redundancy to the structural system. Connections that tie the tops of walls to straight-sheathed roof or ceiling systems, to bond beams, or simply to a parallel wall can tremendously improve the out-of-plane rocking stability of a wall. It appears that such restraints do not need to have great strength, but need only provide continuity throughout the loading cycles and some restoring force near the extremes of the block motions. The restraint is not intended to prevent relative motion between adjacent perpendicular walls, but only to provide some limits so that the positive benefits of rocking motion as a means of dissipating seismic energy can be realized without threatening the stability of the structure.

In-Plane Wall Motion: In-plane wall motions do not typically have the catastrophic consequences or the frequency of occurrence that out-of-plane motions can have. During small to moderate ground motions, in-plane motions typically only amount to small cracks and minor cosmetic damage that can be easily repaired. During larger seismic motions, in-plane wall motions can lead to progressive damage as the broken sections of the wall slide relative to one another. Measures taken to restrict the movements of those blocks will help the overall performance of the structure. These measures can include: anchoring to a continuous member along the top or intermediate locations of a wall,; cables or other members that run the length of walls; end buttresses; or solid framing at doors and windows.

The extent of in-plane displacements that can be tolerated without substantial damage to the structure is considerably smaller than for out-of-plane displacements. Very stiff connections (i.e. a stiff diaphragm) that couples the out-of-plane and in-plane motions of perpendicular walls may result in excessive and unnecessary damage in the in-plane directions because of the substantial difference in the tolerance of adobe walls to out-of-plane motions compared to in-plane motions. The forces required to limit the displacement of the massive out-of-plane walls to those of the in-plane walls will likely exceed the strength of the in-plane walls and may cause excessive damage to the in-plane walls.

This observation is at considerable difference with the conventional observations for masonry walls, where the first concern is for out-of-plane stability. But conventional masonry walls are thin compared to those of adobe. Therefore, their in-plane capacity is considerably higher than their out-of-plane capacity. In such cases, the diaphragm is used to redirect seismic forces from out-of-plane in one wall to in-plane on a perpendicular wall, which is extremely beneficial in improving the seismic performance. Such may also be the case for buildings with thin adobe walls, ones with high height-to-thickness ratios, but is not expected for those that have adobe walls with small height-to-thickness ratios as is typically observed in historic adobes.

"Diaphragm" requirements: In the elastic design of buildings made from either adobe or conventional materials, the diaphragm must be a rather stiff element. The required stiffness of the diaphragm is a function of the amount of out-of-plane deflections that the thin walls can tolerate. The purpose of the diaphragm is to distribute the loads from the out-of-plane walls to the in-plane walls through the diaphragm itself.

"Diaphragm" requirements are different in a thick-walled adobe building. Quotation marks are used around "diaphragm" because the conventionally engineered diaphragm has much stricter strength and stiffness requirements than the "diaphragm" referred to in this discussion. The stiffness of the diaphragm can be considerably less than in conventional thin-walled buildings because the allowable out-of-plane displacements of the thick walls can be tens to hundreds of times larger than the maximum elastic displacements. The principal purpose of the floor and roof systems in a thick-walled adobe building should be not to redistribute loads, but to provide stabilizing forces to the out-of-plane walls.

A "diaphragm" system is expected to improve the in-plane performance of a wall but only when a diaphragm is continuous along the length of a wall and is properly attached to the top of the wall. In this case, the diaphragm may act as an element of continuity that restricts the relative block motions in the plane of the wall.

Connections: Connections are of critical importance in the seismic design of all buildings. The fundamental properties of a well-designed adobe connection are the following:

1. They are durable under cyclic loading.
2. They do not cause major damage to the sur-

rounding adobe. Local failure around an anchor bolt, for example, may serve to dissipate energy, providing improved system performance. Such failure can be acceptable as long as the failure does not cause larger failures that threaten the stability of the connected elements.

3. Attachment or bearing on an adobe surface should be distributed over as large an extended bearing surface as possible.

Connections that join perpendicular walls should be continuous across the structure wherever possible. These connections are best designed if they can accommodate the different in-plane and out-of-plane displacements of adjacent, perpendicular walls. These connections must be attached locally, or the cracking pattern will move just outside the local attachment. This is not to suggest that local attachments cannot serve a purpose, but is intended to emphasize that their primary function is to increase the level at which early cracking develops. Local attachment has a minor to negligible effect on improving global performance during strong seismic motions.

Connections that penetrate through an adobe wall should have bearing plates that distribute the load, preferably in both horizontal and vertical directions. Adobe is a low-strength, brittle material and concentrated loads on wall surfaces should be avoided whenever possible. Connections through walls can tie together some elements of the structure but unless properly detailed are often a source of damage due to the concentration of loads.

Connections should not be so strong as to force connected elements to undergo the exactly the same displacements during seismic response. Some relative motion can be beneficial. This would preclude local yielding of the material and concentrate loads in the weakest element. Adobe buildings are likely to perform best when yielding is allowed and the post-elastic properties of their response are utilized.

Structural Continuity: Structural continuity is provided by elements that can transfer dynamic forces between structural elements in either the vertical or horizontal direction. Structural continuity in adobe, as well as conventional, structures is extremely important for improving their dynamic performance. In thick-walled adobe buildings, the principal need is for elements that provide horizontal continuity among elements, including the blocks likely to be formed as cracking progresses as a result of large ground motions. Gravity forces are the principal means by which forces are transferred in the vertical direction. The substantial mass of adobe walls makes provision of additional continuity in the vertical direction secondary.

The continuous transfer of loads between parallel walls does much to increase the stability of both walls. Continuous elements in the plane of a wall improve the behavior of that wall by restricting the relative displacement of adjacent cracked blocks. Flexible ties can help keep the structure together and functioning as a system if they provide continuity across joints where cracks are expected to develop or already exist.

Compatibility: Compatible elements are those that have similar load-deflection characteristics. When incompatible elements are combined in the same system, large forces can be generated between the incompatible members as the system deforms. In an adobe wall, the incorporation of incompatible materials, such as brick masonry or Portland cement infills, may induce failure modes that typically would not occur if the infills were of adobe. The difference in the modulus of elasticity of adobe and that of either wood or concrete is approximately one order of magnitude.

Cracks regularly form and propagate at the location of material incompatibilities in an adobe wall. In some cases such infills can be used to control the location of first cracking, thereby possibly preventing crack initiation at another location where it would pose a greater threat to the structure's stability or to an important element of the historic fabric. The art of seismic retrofitting an adobe structure very much depends on controlling where and with what consequences yielding occurs. Compatibility concerns, as with other issues, proved both a caution to the designer and a tool for controlling the location of damage.

Redundancy: Redundancy refers to the availability of alternative paths for resolution of earthquake-induced forces in a structure. When there is only one path, the loss of that path can have catastrophic impacts on the structure. When there are several, then the loss of one need not have major consequences. Earthquake engineering is not a precise science, and our ability to predict performance is still limited. As a matter of course, all designers want to provide several paths for force transfer because the state-of-the-art does not allow assurance that if only one is provided the structure will perform as expected. The greater the redundancy, the more confidence there is in satisfactory seismic response.

As an example of redundancy, consider the case where a roof plate is attached to the top of a wall. If the plate is recessed into the adobe, then horizontal restraint of the roof is provided by the adobe buttress of the plate (not a particularly effective connection since unconstrained adobe has little shear capacity) and by friction between the plate and the adobe it bears on. Adding an anchor through the plate into the adobe wall provides an additional way to transfer horizontal loads from the roof to the wall; if many anchors are used, then the other anchors pick up the load from failure of the adobe surrounding one anchor, providing back-up capacity. The addition of the anchors provides redundancy. As a second example, if corbels or interior columns also provide support for the roof's weight, then they provide redundancy, since they can support the roof loads if the walls should fail.

Summary

The purpose of this paper was to shed further light on the seismic retrofitting of historic adobe buildings in a manner that is respectful of their historic fabric. The following observations summarize the principal opinions and conclusions to date:

1. An adobe building is not a conventional building and it is not appropriate to apply conventional engineering analysis and design techniques to these buildings.

2. The successful performance of many historic adobe buildings makes it clear that, under the right circumstances, historic adobe structures can withstand large earthquakes.

3. Repair and maintenance of historic adobe buildings is part of the historical tradition; therefore, repairable damage is acceptable during moderate to large earthquakes.

4. From an engineering perspective, the unique characteristics of adobe buildings can only be fully utilized in withstanding earthquake forces if the adobe buildings are allowed to crack and move. This is distinct from conventional engineering strategies that emphasize "strength-based" designs where cracking is taken to indicate unacceptable performance.

5. Adobe buildings do not necessarily behave in a nonductile, brittle manner, even though they are made from a low-strength, nonductile, brittle material.

6. A thick-walled, cracked adobe building exhibits considerable structural ductility in its seismic response. The low-strength of the adobe and the typical types of cracks that form in the walls result in walls composed of independent cracked blocks. Walls composed of thick, cracked blocks have substantial inherent stability characteristics and their seismic performance can be acceptable if the block movements are managed (restrained) within acceptable limits.

7. The principal objectives of retrofit measures for historic adobe buildings should be to provide: (a) restraints that resist the principal modes of failure (particularly wall overturning); (b) additional restraints that act to hold the blocks in place so that earthquake input energy can be dissipated by wall rocking and sliding friction between adjacent blocks; (c) structural continuity that ties the overall building and its elements together,; and (d) stability for elements (thin walls and gable walls) that are expected to perform unacceptably.

All designers, architects, engineers, regulators and owners should be aware of this last simple fact. Care must be exercised by all to avoid approaching the problems of the seismic safety of historic adobes as if they were conventional buildings. The observed performance of adobes in earthquakes is inherently different than that of conventional, modern construction. It is not surprising, then, that seismic retrofitting of such buildings must be approached by taking advantage of their properties, not by attempting to make adobe perform as if it were concrete, burnt brick or steel.

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