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EARTHQUAKE DAMAGE TO HISTORIC AND OLDER ADOBE BUILDINGS DURING THE 1994 NORTHRIDGE, CALIFORNIA EARTHQUAKE

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SUMMARY

The Northridge, California earthquake of 1994 resulted in losses to several of California's earliest and most culturally significant buildings, its historic adobes. It provided a rare and much needed opportunity for historic preservationists to study the types of damage that occur to soft (unburned clay) masonry buildings as a result of significant earthquakes. This paper summarizes the findings of a damage survey of 20 historic and 9 older abode buildings within the felt area of the earthquake. The findings include an evaluation of performance in relationship to ground shaking intensity and a study of the types of damage sustained.

Based on the data gathered, it appears that ground shaking levels of between 0.1g and 0.2g PGA (between MMI=VI and VI.5) are necessary to initiate damage in well-maintained, but otherwise unreinforced, adobes. Damage of the poorly maintained adobes was greater than that of the well-maintained adobes at similar shaking intensities. Damage state data for retrofitted adobe structures indicate that significantly less damage resulted at the higher PGA (or MMI) levels, but that damage levels similar to those of the unreinforced adobes were experienced at lower PGA levels. Older reinforced adobes performed better at all levels of shaking intensity.

The key to improving structural and life safety performance of California's adobe architectural heritage is understanding how these buildings perform and to direct minimal intervention mitigation efforts to the specific needs and structural behaviors, not to simply tear down and re-build something stronger. The information collected in this survey has helped, and continues to help, in the development of effective retrofit measures that are sensitive to the needs of historic preservationists.

INTRODUCTION

California's historic adobe buildings pay a heavy toll during large earthquakes. The Northridge earthquake was no exception, resulting in the greatest loss to California historic adobes since the 1925 Santa Barbara earthquake. Several of the buildings investigated by a damage survey team (made up of two engineers, a historical architect, and an architectural historian) were subjected to strong ground motions of 0.4g or greater and Modified Mercali Intensity (MMI) values of VIII to IX. Although the loss was tragic, it also presented a rare opportunity to understand and assess the types and levels of damage that occur to these historical and cultural resources during strong ground motion earthquakes.

The earthquake damage information contained in this paper is based on a reconnaissance survey effort, sponsored in part by the Getty Conservation Institute (GCI) [Tolles, et. al., 1996]. The survey was performed in conjunction with the Getty Seismic Adobe Project (GSAP), an on-going multiple-year study with the objective of developing effective seismic retrofit measures for historic adobes with minimal and reversible effects on architectural and structural fabric [Tolles, et al., 1999]. The survey documented damage, and pre-existing

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conditions affecting seismic performance. It also categorized the types of damage in order to validate GSAP shake-table test results, and to aid in the development of effective retrofit measures.

EVALUATION OF SEISMIC PERFORMANCE

The Northridge earthquake had a Richter magnitude of ML=6.4, a surface wave magnitude of Ms=6.8 and a seismic moment of Mw=6.7. The rupture initiated approximately 12 miles (19 km) below the San Fernando Valley (a shallow earthquake) and propagated upward toward the northeast. The location of the epicenter was approximately one mile (1.6 km) southwest of the community of Northridge.

Although the local Richter magnitude of this earthquake was only 6.4, the intensity of shaking in several areas was very strong. In the epicentral region, as well as another area to the north, the maximum intensity on the Modified Mercali scale was IX. The duration of the strong motion was about 10 to 15 seconds and is comparable to the duration of the devastating 1971 San Fernando earthquake, but significantly shorter than the 1992 Landers earthquake, which lasted approximately 30 seconds.

Damage was not only concentrated in the epicentral region, as expected, but several other areas were hard hit as well, including the Sherman Oaks/Encino area, central Los Angeles just south of the Santa Monica freeway, Santa Monica, the Santa Clarita Valley, and Fillmore in the Santa Clara River area. Most of the historic and older adobes included in this survey were located in these soft-soil areas.

Estimates of MMI and peak ground acceleration at each of the 20 historic and 9 older adobe sites included in the survey were determined based on: 1) the MMI isoseismal contour map shown in Volume 1 of the EERI reconnaissance report [EERI, 1995]; 2) California Strong Motion Instrumentation Program strong-motion recording station data [Shakal, et. al., 1994]; and 3) the isoseismal maximum horizontal ground acceleration map developed by the University of California at Berkeley [Stuart, et. al., 1994]. Locations, epicentral distances, ground shaking intensities and damage states for the 20 historic adobes are listed in Table 1. Similar information is listed in Table 2 for the nine older adobes (built between 1910 and 1960).

To correlate damage with ground shaking intensity, damage state definitions were adopted from EERI and modified specifically for historic and older adobe buildings (see Table 3). There is nothing particularly precise about these damage state descriptions, but they do give a measure of the relative performance of each of the adobes in the survey. Damage state definitions were developed by EERI for the purpose of comparing relative damage levels in unreinforced brick masonry buildings. Table 3 lists the "Standardized Damage States", A through E, with their EERI descriptions. A third column includes commentary on these damage states relative to historic and older adobe buildings. Using the EERI scale, the overall seismic performance of each of the 29 buildings was rated by the survey team and the results listed in Tables 1 and 2.

Plotting damage versus peak ground acceleration (PGA) for these 29 buildings proves to be quite informative. Figure 1 is a scattergram plot for the unreinforced, but well maintained, historic and older adobes (16 out of the 29 surveyed). These buildings had insignificant pre-existing conditions, thus excluding adobes with:

- Unrepared or poorly repaired crack damage;
- Severe water intrusion damage;
- Seismic retrofits or upgrades;
- Reinforcing.

The plot also includes a linear least-squares “best estimate” relationship of damage to PGA. In addition to giving basic seismic fragility information for unretrofitted historic adobes in good condition, this straight-line estimate serves as a baseline by which to judge the performance of adobes either suffering from or enhanced by pre-existing conditions. Even though there is considerable scatter of the data about the expected damage (“best estimate”) line, indicating the influence of many other factors, some trends are reasonably clear.

First, it appears that PGA in the range of 0.1g to 0.2g is needed to initiate damage in the well maintained, but otherwise unreinforced adobe buildings. At this level of shaking, cracks will begin to form at door and window openings and at the intersections of perpendicular walls. The damage levels increase with increases in PGA. At a PGA of about 0.4g the damage is moderate to extensive and includes more general crack damage throughout the structure.

Table 1: Historic adobe buildings examined after the Northridge earthquake

Historic Adobe Name/ Location	**Distance/ Direction from**	**PGA (est.)**	**MMI (est.)**	**DAMAGE STATE**	**PRE-EXISTING**
Andres Pico Adobe Mission Hills	5 miles (8 km) northeast	0.5g	VIII-IX	D-E	Poor Maintenance
San Fernando Mission Convento Mission Hills	5 miles (8 km) northeast	0.5g	VIII-IX	C-D	Seismic Retrofit
Centinela Adobe Winchester	20 miles (32 km) southeast	0.2g	VII	B-C	
De la Osa Adobe Encino	5 miles (8 km) southeast	0.4g-0.5g	VIII	D-E	
Antonio Jose Rocha Adobe Park La Brea	15 miles (24 km) southeast	0.3g-0.4g	VII	B-C	
Leonis Adobe Calabasas	7 miles (11 km) southwest	0.3g-0.4g	VII	C-D	
Lopez Adobe San Fernando	7 miles (11 km) northeast	0.5g	VIII	C	Seismic Retrofit
Lopez-Lowther Adobe San Gabriel	27 miles (43 km) southeast	0.2g	VI-VII	C-D	Poor Maintenance
Miguel Blanco Adobe San Marino	27 miles (43 km) southeast	0.1g-0.2g	VI	A	
Pio Pico Mansion Whittier	32 miles (51 km) southeast	0.1g-0.2g	VI-VII	B-C	Seismic Upgrade
Rancho Camulos Piru	18 miles (29 km) northwest	0.4g	VII-VIII	D-E	Poor Maintenance
Reyes Adobe Agoura Hills	15 miles (24 km) southwest	0.2g-0.3g	VIII	B-C	Seismic Retrofit
San Gabriel Mission Convento San Gabriel	27 miles (43 km) southeast	0.2g	VI-VII	D	Poor Maintenance
San Rafael Adobe Glendale	17 miles (27 km) southeast	0.3g	VI-VII	C	
Sepulveda Adobe Calabasas	12 miles (19 km) southwest	0.2g-0.3g	VI-VII	C-D	Poor Maintenance
Simi Adobe Simi Valley	14 miles (22 km) northwest	0.2g-0.3g	VII	C	
Las Tunas Adobe San Gabriel	27 miles (43 km) southeast	0.2g	VI-VII	B	
Vicente Sanchez Adobe Crenshaw	19 miles (30 km) southeast	0.2g-0.3g	VII	C	
Plaza Church Los Angeles	21 miles (34 km) southeast	0.2g	VII	A-B	
Catalina Verdugo Adobe Glendale	18 miles (29 km) southeast	0.3g	VII	A-B	

Figure 2 is a scattergram plot of damage for those adobes with the pre-existing conditions listed above (13 out of 29 surveyed). Relative to the “best estimate” damage state relationship for unreinforced, but well maintained adobes, pre-existing conditions have definite effects on the resulting damage states. Obviously, the poorly maintained adobes consistently fared worse than well-maintained adobes. Even at moderately intense ground motion (0.1g to 0.2g) poorly maintained adobes are likely to suffer substantial damage.

Not so obvious, because of the sparse data, is the effect that seismic retrofits or upgrades have on the performance of historic and older adobes. As a preliminary conclusion from Figure 2, it appears that the value of seismic retrofitting or upgrading is not realized until relatively high levels of ground shaking occur (i.e., above 0.3g). At lower levels of ground shaking, the retrofit measures appear not to affect performance. At these lower levels of ground shaking, the retrofitted buildings behave much the same as well maintained, unretrofitted adobes. Similar performance has been observed in model tests conducted by the GSAP [Tolles, et. al., 1993 and 1999].

The reinforced adobe buildings show an even greater resistance to damage than those that have been retrofitted. At all levels of ground shaking there was less damage suffered by the reinforced adobes than was observed in the well maintained, unreinforced adobes. This can likely be attributed to the use of a portland cement based mortar and grout in the construction of these walls, which appears to stiffen the structures relative to adobe buildings constructed using traditional mud based mortar. The cement-based mortar allows less movement, and therefore less damage at lower levels of ground motion.

Table 2: Older adobe buildings examined after the Northridge earthquake

Type of Building/ Location	*Distance/ Direction from Epicenter*	*PGA (est.)*	*MMI (est.)*	*Damage State*	*Pre-existing Condition*
Single-story residence Northridge	*1 mile (1.6 km) west*	*0.5g*	*VIII-IX*	*C*	*Reinforced*
Single-story residence Northridge	*0.5 miles (0.8 km) north*	*0.6g*	*IX*	*D*	
Church San Fernando	*8 miles (13 km) northeast*	*0.4g-0.5g*	*VIII*	*A-B*	*Reinforced*
Single-story residence Encino	*6 miles (10 km) southeast*	*0.3g-0.4g*	*VIII*	*C-D*	
Two-story residence Burbank	*13 miles (21 km) southeast*	*0.3g-0.4g*	*VIII*	*C-D*	
Two-story residence Santa Monica	*17 miles (27 km) south*	*0.6g-0.7g*	*VIII*	*D*	
Two-story residence Santa Monica	*18 miles (29 km) south*	*0.6g-0.7g*	*VIII*	*D*	
Single-story residence Sylmar	*9 miles (14 km) northeast*	*0.5g-0.6g*	*VIII*	*B-C*	*Reinforced*
Single-story residence Manhattan Beach	*25 miles (40 km) southeast*	*0.1g-0.2g*	*VI*	*A-B*	*Reinforced*

Table 3: EERI Standardized Damage States

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

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

[2] Times are difficult to assign because they are largely dependent on the size of the building.

DAMAGE TYPOLOGIES

Generic or standardized damage states are extremely useful in performing seismic risk studies or cost-benefit analyses of seismic retrofit programs for historic structures. However, directing seismic retrofit mitigation efforts to counteract the damaging effects of future earthquakes on historic and older adobes, requires understanding the specific types of damage that occur to these buildings. The extent of damage to an adobe structure subjected to an earthquake is, in simple terms, a function of: 1) the severity of the ground motion; 2) the geometry of the structure, i.e., the configuration of the walls, roof, floors, openings and foundations systems; 3) the overall integrity of the adobe masonry; 4) the existence and effectiveness of various seismic retrofit measures; and 5) the condition of the building at the time of the earthquake. The more important types of damage that result from or are significant to the seismic performance of historic and older adobe buildings are shown in Figure 3, and are discussed in the following sections

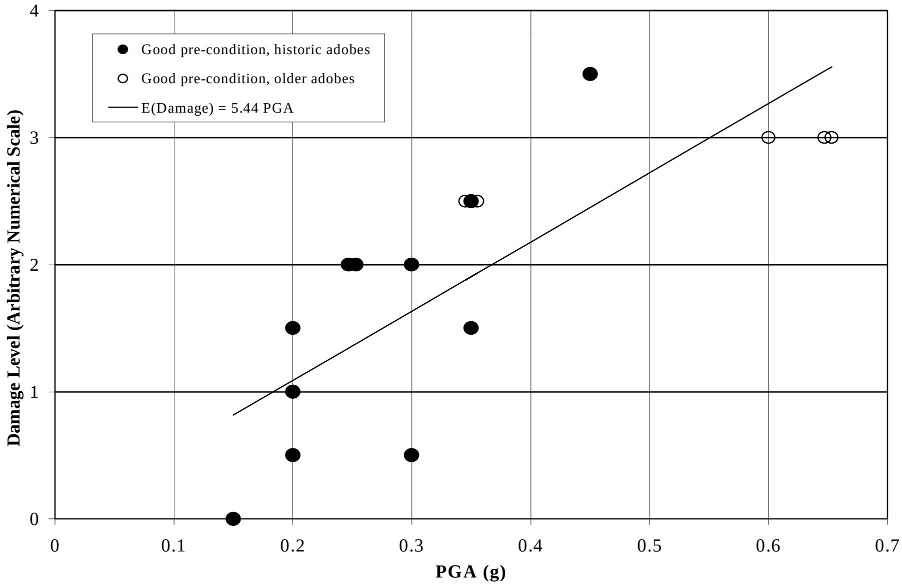

Figure 1: Damage versus Peak Ground Acceleration for historic and older unreinforced and well-maintained adobes

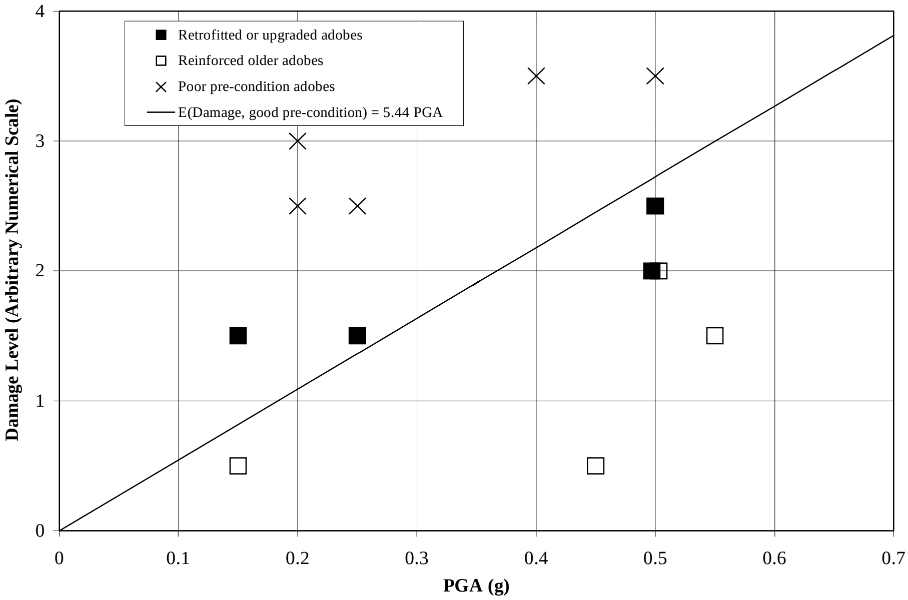

Figure 2: Damage versus Peak Ground Acceleration for adobes other than unreinforced and well maintained.

Out-of-Plane Flexural Damage

Adobe walls are quite susceptible to crack damage resulting from out-of-plane flexural stresses. Out-of-plane crack damage initiates as a vertical crack at the intersection of a perpendicular wall, extending vertically or diagonally and running horizontally along the base between transverse or intersecting walls. The wall rocks back and forth out-of-plane, rotating about the horizontal crack at the base. Although cracks from out-of-plane forces occur readily in these buildings, the extent of damage is often not severe, as long as there is adequate support provided by the floor and/or roof diaphragm.

Gable-Wall Collapse

The collapse of gable-end walls is a special case of out-of-plane flexural damage and a damage type all too often observed in historic adobe buildings as a result of strong ground motion. Gable walls are tall, slender and usually not well supported laterally. Unless anchored to the roof diaphragm, they can slip out from underneath the roof framing, as occurred at the Andres Pico and De la Osa adobes during the Northridge earthquake.

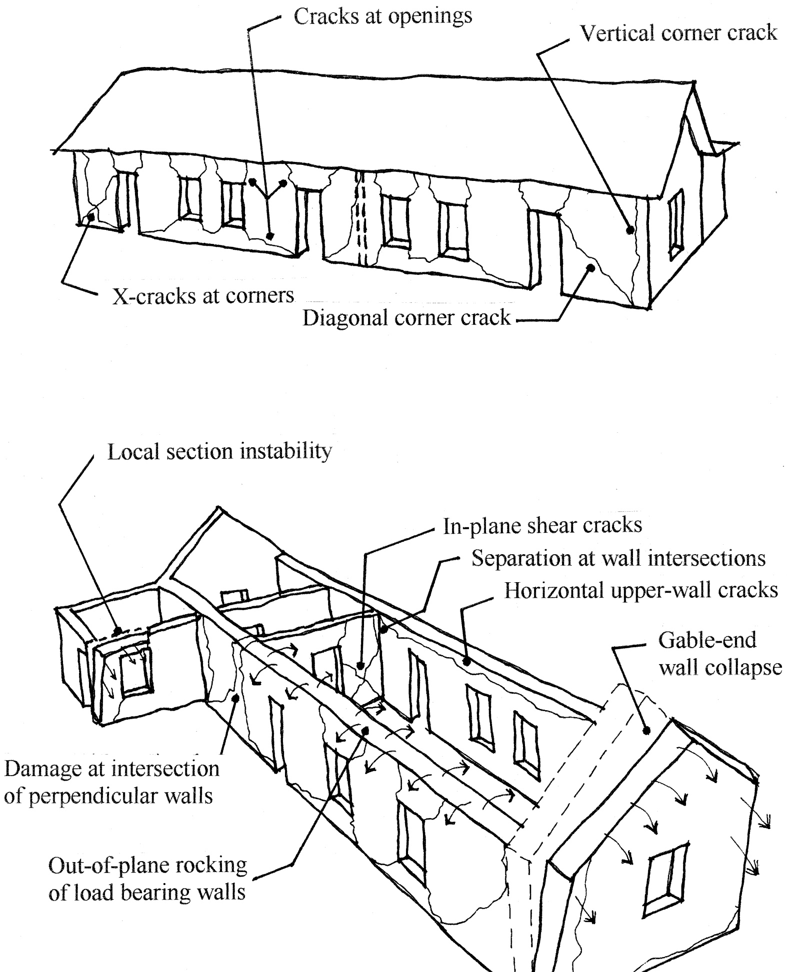

Figure 3: Typical types of damage observed in historic adobe buildings after the Northridge earthquake

Separation Damage

Separation of longitudinal walls at their intersection with perpendicular cross walls is a common type of damage, which also results from out-of-plan movement of the walls. As the longitudinal wall rocks outward it pulls away from intersecting perpendicular walls, creating tensile stresses at these junctures that easily crack the adobe. In many cases there is no physical connection at the intersections of walls, having been constructed simply as abutting. The discontinuity that exists at the juncture becomes larger as the longitudinal wall rocks. Examples of this type of damage were numerous in the surveyed buildings.

Tie-Rod Anchorage Failure

In a prior attempt to counteract separation of the longitudinal walls from the transverse walls, the De la Osa adobe had tie rods installed across five of its transverse interior walls. These tie rods were round steel bars in some cases and wooden beam elements in others, installed near the top of the wall. They were all anchored to the exterior surface of the longitudinal walls. Some anchors failed, partially pulling through the exterior surface of the longitudinal wall and allowing separation at the wall intersections. In two instances the tie-rod anchorage held and the longitudinal wall remained tight against the transverse cross wall.

Horizontal Upper-Wall Damage

Damage can also occur to the upper portion of a longitudinal wall as a result of the out-of-plane movement where the roof bears on top of the wall. Included in this category are slippage of the top plate and displacement of the top course or two of adobe blocks. Slippage of the ceiling framing can also occur. This type of damage is due to the very limited friction force that is generated by the roof weight bearing down on the top of the wall and the friable nature of historic and older adobe block construction.

Wall slippage can also occur in older adobes with concrete bond beams. The top of the wall may slip out from underneath the bond beam when there is not enough weight from above to hold the wall in place by friction during lateral movement.

Wall Mid-Height Flexural Damage

For the most part, historic adobe structures are not susceptible to mid-height out-of-plane flexural damage. However, in those few cases (e.g., the convento at San Fernando Mission) where the load-bearing walls are long, tall and slender, horizontal crack damage at mid-height can occur due to out-of-plane ground motion.

Although the exterior longitudinal walls of the San Fernando convento are relatively thick, the thickness is comprised of two independent wythes, with no masonry header courses to inter-connect them. Although the inner wythe of the north longitudinal wall of the convento was anchored to the second-floor diaphragm prior to the Northridge earthquake, the outer wythe acted as an independent, very long, two-story wall, and a mid-height horizontal crack developed along its length. The crack damage from this out-of-plane movement is not serious. However, the potential for much greater damage is significant.

Diagonal Crack Damage

In-plane diagonal cracks and X-diagonal cracks result from shear forces in the plane of the walls. These cracks are not particularly serious unless the relative displacement across them becomes large. They do represent a lessening of the lateral stiffness of the building. But unless a segment of the wall on one side of the crack is in danger of loosing purchase on the adjacent segment, the gravity load path remains in tact.

Corner Crack Damage

Diagonal cracks in exterior walls at building corners are more serious than within the main body of the wall since they form wedges that can easily move sideways and downward as the building shakes. Other corner crack patterns include vertical cracks on one or two perpendicular faces, resulting from out-of-plane movement of one or both walls. If there are two vertical cracks, one on each perpendicular face, this leaves a freestanding column of adobe at the corner, which is quite vulnerable to collapse.

Crack Damage at Openings

The most common type of crack damage is that occurring at the corners of door and window openings. These cracks can occur at PGA levels as low as 0.1g to 0.2g and are a result of both in-plane shear forces and out-of-plane flexure of the wall. They are not particularly serious unless the relative displacement across the cracks is large, in which case instability of the section of wall above the opening becomes an issue.

Moisture Damage

Although not shown in Figure 3, water intrusion at the base of adobe walls often results in excessive spalling of plaster and adobe as the wall rocks out-of-plane and compresses the outer wall surface. Water is the most prevalent threat to adobe buildings in areas of both high and low seismicity. Basal erosion occurs from rain splash against the wall or rising damp from the surrounding foundation soil. This erosion can remove material at the base of the wall that can eventually lead to instability.

The strength of the adobe material becomes a concern when it has been affected by water. Wet adobe walls can easily reach the plastic limit and begin to deform under their own weight. Also, repeated wet-dry cycles reduce the strength of the adobe so that, even when dry, a wall may be weaker than when originally constructed. When the adobe material at the base of a wall is weakened by moisture intrusion, a through-wall shear plane develops, along which the upper portion of the wall can slip and collapse. This type of failure was instrumental in the collapse of walls at the Andres Pico adobe, and the Del Valle adobe at Rancho Camulos during the Northridge earthquake.

CONCLUSION

The information obtained by the survey team regarding the seismic behavior and performance of historic and older adobes is invaluable to the development of appropriate, cost-effective, and minimally intrusive retrofit measures (see [Tolles, et al., 1996] for more complete details on historic adobes). Categorization of the types of damage allows an evaluation of the causes and criticality of such damage types, so that effective retrofit measures may be developed and implemented. In deed, this information, in conjunction with the GSAP shake table testing [Tolles, et al., 1999] of 1:5 and 1:2 adobe model buildings, has been and is being used to develop appropriate seismic retrofit measures that ensure adequate life safety, while protecting historic fabric and cultural value.

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

REFERENCES

EERI (1995), "Northridge Earthquake Reconnaissance Report, Vol. 1", Supplement C to Volume 11 of Earthquake Spectra, Earthquake Engineering Research Institute, Oakland, California.

Stuart, J.P., Bray, J.D., Seed, R.B. and Sitar, N. (1994), Preliminary Report on the Principle Geotechnical Aspects of the January 17, 1994 Northridge Earthquake, Earthquake Engineering Research Center, College of Engineering, University of California at Berkeley, Berkeley, California.

Shakal, A., Huang, M., Darragh, R., Cao, T., Sherburne, R., Malhotra, P., Cramer, C., Sydnor, R., Graizer, V., Maldonado, G., Petersen, C. and Wampole, J. (1994), CSMIP Strong-Motion Records from the Northridge, California Earthquake of 17 January 1994, Report No. OSMS 94-07, California Department of Conservation, Division of Mines and Geology, Sacramento, California.

Tolles, E.L., Kimbro, E.E., Thiel, C.C., Webster, F.A. and (1993), Getty Conservation Institute Guidelines for the Seismic Retrofitting of Adobe Project: Report of Second Year Activities, The Getty Conservation Institute, Los Angeles, California.

Tolles, E.L., Webster, F.A., Crosby, A. and Kimbro, E.E. (1996), Survey of Damage to Historic Adobe Buildings After the January 1994 Northridge Earthquake, GCI Scientific Program Report 1996, The Getty Conservation Institute, Los Angeles, California.

Tolles, E.L., Kimbro, E.E., Webster, F.A., and Ginell, W.S. (1999), The Getty Seismic Adobe Project, Final Report, The Getty Conservation Institute, Los Angeles, California.