Getty Seismic Adobe Project Research and Testing Program

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Abstract: *During the 1990s the Getty Conservation Institute (GCI) funded the Getty Seismic Adobe Project (GSAP), a multidisciplinary research effort to develop effective seismic retrofit measures that have a minimal impact on the significant historic fabric of historic adobe buildings.*

The early stages of the research included a field survey of common architectural types of historic adobe buildings, a survey of common practices of retrofitting historic adobe buildings in the United States, a review of technical literature, and a review of studies of the damage to historic adobe buildings. The major lack of basic information was in the area of documentation of the details of actual earthquake damage to historic adobe buildings.

The 1994 Northridge earthquake was a significant opportunistic event for this research project. During that event, the historic adobe buildings near Los Angeles suffered significant damage. The damage to more than a dozen historic adobe buildings was documented and published in 1996. This field study also included an overview and analysis of the typical types of seismic damage that occur in historic adobe buildings in this region.

A substantial portion of the research effort was dedicated to shake table testing of reduced-scale models of adobe walls and adobe buildings. Nine small-scale buildings (1:5 scale) were tested at Stanford University, in Palo Alto, California. Two large-scale models (1:2 scale) were tested at the research facility of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University "SS. Cyril and Methodius" in Skopje, Republic of Macedonia. The testing program was used to evaluate the effectiveness of a range of seismic retrofit measures, including vertical and horizontal straps, vertical center core rods, anchorage at the roof and floor line, and the use of bond beams.

The final part of the project was to develop engineering design guidelines for the retrofit of historic adobe buildings. The engineering guidelines were combined with planning guidelines and published together as part of the final publication of the GSAP.

Introduction

The Getty Seismic Adobe Project was a multiyear project of the Getty Conservation Institute to develop structurally effective seismic retrofitting strategies for historic adobe buildings that have minimal and, to the extent possible, reversible impacts on historic fabric. This project included a survey of historic adobe buildings in California, preparation of planning guidelines for retrofitting historic adobe buildings, performance of tests of model adobe buildings on an earthquake simulator, a survey of damage to historic adobe buildings after the 1994 Northridge earthquake, and preparation of engineering guidelines for the retrofit of historic adobe buildings. Additional large-scale earthquake simulator tests were performed at IZIIS.

Background Research

The goal of this research program was to determine means of seismic retrofitting for historic adobe structures that have a minimal effect on the historic fabric of

the buildings. Two issues form the theoretical basis for this research program:

1. *Stability-based measures:* The seismic performance of unreinforced adobe buildings can be greatly improved by the use of minor restraints and elements of continuity that inhibit the relative displacements of cracked wall sections and prevent the principal modes of failure.

2. *Slenderness ratio and wall thickness:* The slenderness (height-to-thickness) ratio (S_L) is of fundamental importance in determining the behavior of unreinforced masonry in general and adobe in particular. The slenderness ratio will affect the susceptibility of an adobe building to damage and affect the type of retrofitting measures that may be appropriate.

Both of these issues have been addressed by shake table tests on reduced-scale models, by studies of observed damage to adobe buildings after the Northridge earthquake, and by testing performed on large-scale model buildings.

Earthquake Damage Assessment of Historic Adobes

The damage to more than a dozen historic adobe buildings that resulted from the 1994 Northridge earthquake
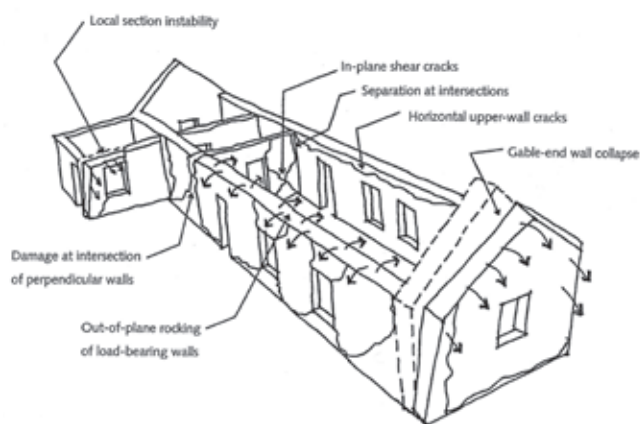

FIGURE 1 Typical damage to historic adobe buildings, as observed after the 1994 Northridge, California, earthquake.

was studied and documented as part of the overall GSAP program (Tolles et al. 1996). Each of the buildings was studied, and the type of damage was documented. The overall set of damage was itemized to characterize the types of damage that may occur to historic adobe buildings, as shown in figure 1.

Laboratory Research

The GSAP laboratory research included both small-scale and large-scale models tested on dynamic earthquake simulators. The ground motion for the tests was based on actual earthquake records from historic earthquakes recorded in California. The small-scale tests were carried out on 1:5 scale adobe buildings, and the large-scale tests were performed on 1:2 scale adobe buildings. Test results were published in 2000 (Tolles et al. 2000).

Small-Scale Models

Three 1:5 scale adobe models (group A: models A1, A2, and A3) were tested during 1992–93. The tests on these models were designed to address the first issue—i.e., the effectiveness of stability-based retrofit techniques. These tests clearly demonstrated that the use of stability-based retrofit measures can dramatically improve the seismic performance of an adobe building. Each model was subjected to a series of up to ten shake table motions, in which each test was approximately 30% larger than the previous test, as listed in table 1. A listing of all model buildings tested is presented in table 2.

Models 4, 5, and 6 were designed to address the second issue, the effects of wall slenderness. The walls of model 4 had a slenderness ratio of 5. The walls of models 5 and 6 had slenderness ratios of 11.

The results of the tests on models 1 through 6 indicated that the thickness of adobe walls has an effect on the seismic performance but that it is of secondary importance compared to the improved performance provided by the implemented stability-based retrofitting measures.

Model 7 was the first building designed as a complete building, with gable-end walls and floor and roof framing. The retrofitting measures were designed to address many of the issues that may occur in an actual building and to assess the performance of a larger, more

Table 1 Simulated earthquake motions for testing model buildings (prototype dimensions). EPGA = estimated peak ground acceleration (Tolles and Krawinkler 1990)

Test level	Maximum EPGA (g)	Maximum displacement (cm)	Maximum displacement (in.)
I	0.12	2.54	1.00
II	0.18	5.08	2.00
III	0.23	7.62	3.00
IV	0.28	10.16	4.00
V	0.32	12.70	5.00
VI	0.40	15.88	6.25
VII	0.44	19.05	7.50
VIII	0.48	25.40	10.00
IX	0.54	31.75	12.50
X	0.58	38.10	15.00

complex building with the application of stability-based measures.

The plan layout of model 7 was similar to the layout of the first six models. In model 7, floor joists were added at the level of the tops of the walls of models 1 through 6. The basic layout of model 7 was based on typical *tapanco*-style adobe construction. The load-bearing walls of *tapanco* style adobe buildings extend approximately 3 ft. (1.0 m) above the attic floor, and there are gable-end walls at the non-load-bearing ends (east and west) of the building.

In models 7, 8, and 9, the walls extended four courses (approximately 2 ft., or 0.65 m, in prototype dimensions) above the attic floor. The load-bearing (north and south) walls have a door and a window in each wall. The gable-end (east and west) walls extend above the north and south walls at a slope of 6:12 vertical to horizontal. The wall elevations of model 9 are shown in figure 2.

The retrofitting measures used on model 7 were based upon the more successful measures tested in models 1 through 6, with the addition of partial diaphragm measures used on the attic floor and roof system. The retrofitting system used consisted primarily of the following: (1) horizontal and vertical straps applied to the walls, and (2) partial wood diaphragms applied to the attic floor and roof. The remainder of the retrofit system consisted of connection details.

A combination of vertical and horizontal straps was applied to all the walls. As had been implemented on previous models, the retrofitting strategy is slightly different on the west and south walls, compared to that implemented on the east and north walls.

Two horizontal straps were placed on each of the four walls. The upper horizontal strap was located at the attic floor line, and the lower horizontal strap was located just below the bottom of the window. The strap at the attic floor line ran around the perimeter of the building and was attached to the floor system. The attachments to the floor system are shown in the details in figures 3 and 4. The lower horizontal strap was located on both sides of each of the walls. Smaller straps were used as cross-ties to connect the straps on both sides of the wall.

On the west wall, no vertical straps were added. The west and east walls had no door and window openings, except for small attic windows. The south wall had only one vertical strap located at the center of the pier between the door and the window. The north and east walls had vertical straps at regular intervals (see fig. 2).

The vertical straps were located on both sides of each wall. The straps went over the tops of the walls and through
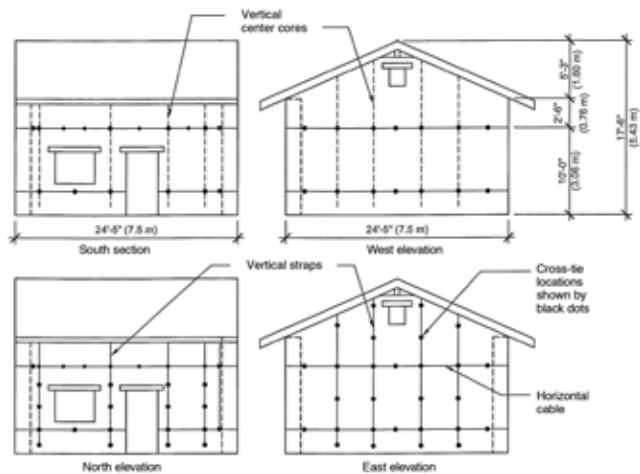

FIGURE 2 Wall elevations of model 9, with vertical straps on the north and east walls and center core rods on the south and west walls. Note that dimensions are prototype dimensions.

Table 2 Description of models tested. Models 10 and 11 were tested at IZIIS; all other models were tested at Stanford University

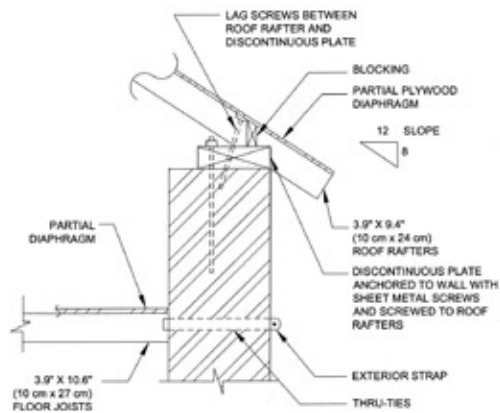| Model no.	Slenderness	Scale	Walls	Description of retrofit strategy
1	7.5	1:5	NE	Upper horizontal strap
			SW	Upper and lower horizontal straps
2	7.5	1:5	NE	Bond beam and center cores
			SW	Bond beam plus vertical and horizontal straps
3	7.5	1:5	NE	Bond beam, center cores, and saw cuts
			SW	Bond beam, center cores, and lower horizontal straps
4	5	1:5	NE	Upper strap
			SW	Upper and lower horizontal straps
5	11	1:5	NE	Unretrofitted control model for model 6
			SW	Unretrofitted control model for model 6
6	11	1:5	NE	Bond beam, lower horizontal straps, and vertical straps
			SW	Bond beam, lower horizontal straps, and local ties
7	5	1:5	NE	Partial diaphragm applied on attic floor and roof framing and lower horizontal and vertical straps
			SW	Same as the NE walls, except vertical straps placed only on the piers between the door and window on the north wall
8	7.5	1:5	NE	Vertical straps on north and east walls only
			SW	Vertical center core rods in south and west walls only
			Both walls	Partial diaphragms applied to the attic floor and roof framing. Horizontal strap at the floor line anchored to floor diaphragm. Lower horizontal straps.
9	7.5	1:5		Unretrofitted control model for model 8
10	7.5	1:2		Unretrofitted control model for model 11
11	7.5	1:2	NE	Vertical straps on north and east walls only
			SW	Vertical center core rods in south and west walls only
			Both walls	Partial diaphragms applied to the attic floor and roof framing. Horizontal strap at the floor line anchored to floor diaphragm. Lower horizontal straps.

FIGURE 3 For models 7 and 9, connection and roof and floor partial diaphragms at load-bearing walls. Note that dimensions are prototype dimensions.
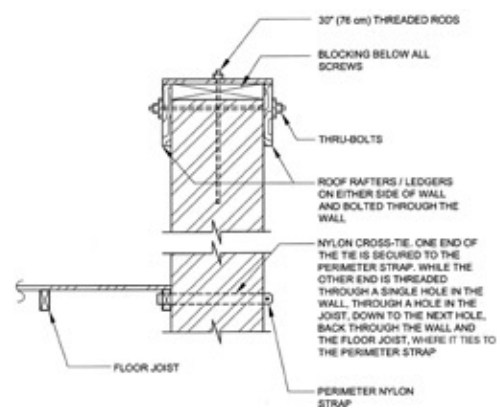

FIGURE 4 For models 7 and 9, connection between walls and diaphragms at non-load-bearing walls. Note that dimensions are prototype dimensions.
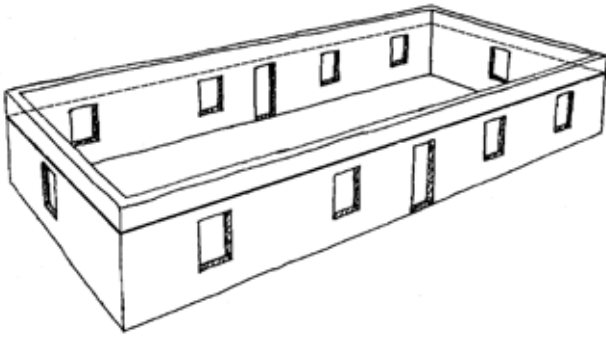
FIGURE 5 The upper wall element of a typical retrofit system.

drilled holes at the base of the walls. Small-diameter nylon cord was used for cross-ties on these straps, similar to those used with the lower horizontal straps.

Partial wood diaphragms were added to the attic floor and roof. The width of the diaphragm on the attic floor was approximately 8 in. (0.20 m), equivalent to the spacing between the floor joists. Additional straps were added to the attic diaphragm for continuity, as shown in figure 5. The width of the partial roof diaphragm was approximately 6 in. (0.15 m).

On the load-bearing walls (see fig. 3), the bearing plates on the tops of the wall were discontinuous so that they did not act as bond beams. These bearing plates were cut into four sections on top of the north and south walls. The bearing plates were anchored to the walls with 3 in. (7.6 cm) sheetrock screws. The roof rafters were anchored with screws to the bearing plates, and blocking was placed between each of the roof rafters.

The floor joists were anchored to the walls with small-diameter cord. This cord went through a hole drilled through the center of the floor joist. The cord went through the adobe wall on either side of the joist and attached to the horizontal strap on the exterior face of the wall.

On the non-load-bearing walls (see fig. 4), the roof rafters were placed directly on either side of the wall and tied together with bolts through the wall. The partial roof diaphragm was attached to the tops of the roof rafters. Six-inch (15.2 cm) screws extended through the roof diaphragm and the blocking below the diaphragm and extended into the wall. The purpose of these details was to tie the tops of the gable-end wall to the roof system.

These connections worked well and did not fail during the tests.

Overall, the performance of model 7 and the behavior of the retrofit measures was extremely good. From observation of the videotapes, it appeared that substantial sections of the models might have collapsed during test level VI or VII. Instead, model 7 performed well through test level X. Only a lightly retrofitted section of the south wall collapsed during the first repetition of test level X. The out-of-plane performance of both gable-end walls was particularly impressive, as neither end collapsed.

The important aspects of the performance of model 7 are as follows:

1. The model behaved very well and generally as expected, based upon the results of the previous six model tests. The retrofitting system used on this model was clearly a success.
2. The cracking pattern was generally as predicted. The vertical and horizontal straps with cross-ties at regular intervals behaved well, even when cracks did not occur where they were expected.
3. The roof diaphragm was sufficiently stiff to prevent out-of-plane collapse of the gable-end walls. Large displacements occurred at the tops of these walls because of the flexibility of the diaphragm system, but the restraint was sufficient to prevent collapse. The roof diaphragm was particularly flexible because of the break in the diaphragm that occurred at the ridge line.
4. The horizontal diaphragm at the attic level was considerably stiffer than the roof diaphragm. The through-wall connections performed well during the tests. Horizontal cracks developed in the two gable-end walls because of the out-of-plane motions of these walls.
5. Permanent displacements of 1–2 in. (2.5–5.1 cm) occurred at the horizontal cracks in the east and west walls during tests 8, 9, and 10. The retrofitting system was sufficient to prevent collapse of these walls but not to prevent this amount of displacement.
6. The lower horizontal straps worked effectively to prevent the deterioration of the piers under

the windows. In most of the models and as expected, diagonal cracks extended from the lower corner of the windows to the corner of the building, but the straps prevented substantial widening of these cracks.

Models 8 and 9 were constructed to be nearly the same as model 7, except that the S_L ratio was 7.5. Model 9 was unretrofitted. Both gable-end walls collapsed during test 6. The west gable end would have collapsed during test 5, except for the moderate restraint provided by the roof system. Model 8 was retrofitted similarly to model 7. The retrofitting schemes on the north and east walls were nearly identical to those of model 7, with both vertical and horizontal straps. The south and west walls of model 8 had ¼ in. fiberglass center core rods (0.25 in., or 0.6 cm) placed in epoxy grout in 0.375 in. (1.0 cm) holes. Model 8 behaved well through test 10, with substantial damage but with limited offsets and no collapsed sections. The walls with fiberglass center cores behaved particularly well and sustained only minor damage.

Large-Scale Models

The two large-scale models (models 10 and 11) tested in IZIIS in Macedonia were built for direct comparison to models 8 and 9, tested at Stanford. These two models were one-half the size of the prototype building. The first model tested at IZIIS (model 10) was an unretrofitted building, and the second model (model 11) was retrofitted as the smaller scale model (model 8), using a combination of partial diaphragms, horizontal cables, vertical straps, and vertical center core rods.

Guidelines

The final product of the GSAP research effort in the 1990s was the *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures* (Tolles, Kimbro, and Ginell 2002).

Before plunging into the retrofit design process, the design team must devote some effort to identifying the goals that can be attained by retrofitting. Decisions must be made about the goals of the retrofitting system and how those goals might be achieved. The minimum level of intervention must provide for life safety in and around a building, but other goals for structural per-

formance may be considered. The design may be geared toward preventing collapse or other life-safety hazards during the largest seismic events, but it may also be directed toward the minor damage that may occur during more moderate earthquakes.

Global Design

The starting point in the design process is an understanding of the basic elements necessary for global performance. Restraint at the tops of walls to prevent out-of-plane collapse is the first consideration of a retrofit design. A flexible diaphragm or other measures that prevent out-of-plane failure may be all that is necessary to prevent the collapse of many thicker-walled adobe buildings. Vertical wall elements (center cores or straps) may also be considered, to prevent collapse of thinner walls; vertical wall elements can also add ductility or strength to any adobe wall. Lower wall elements can add additional tensile capacity to an adobe wall for protection against progressive types of failures. Figure 5 is a diagram of an adobe building with upper wall cables; the drawing could also represent a partial or flexible roof or floor diaphragm. Figure 6 shows the addition of vertical straps to the retrofit system.

Crack Prediction

Schematic diagrams of a building with possible variations of cracks that are likely to occur during seismic events or that may occur from foundation settlement
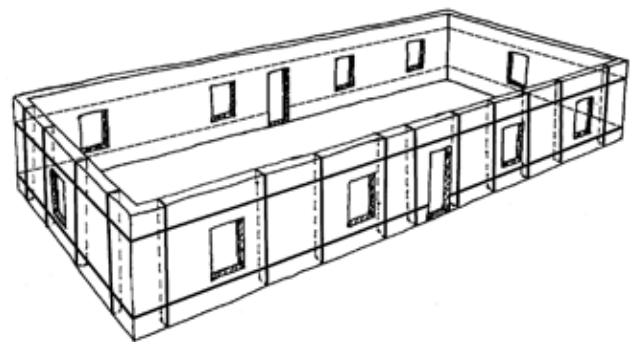

FIGURE 6 Vertical straps on the two adjacent walls, in addition to upper and lower horizontal straps.
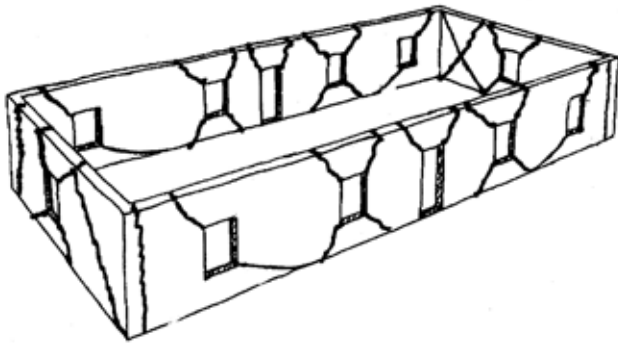
FIGURE 7 Typical predictive crack pattern for identification of wall sections that will require stabilization during strong ground motions.

can be a very useful tool in determining the possibilities of local wall failures. Each section of wall bounded by cracked elements can be a potential hazard to building occupants. Therefore, each cracked wall section should be stabilized by the retrofit system. Possible cracked wall elements are shown in figure 7.

Specific Retrofit Measures

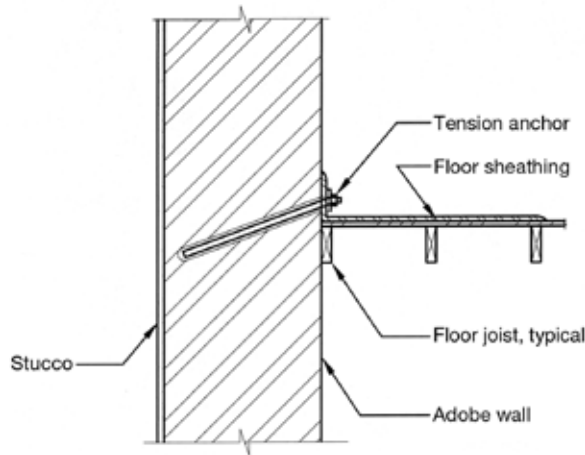The specifics of retrofit measures should address many different issues. These issues include out-of-plane design of the adobe walls, in-plane design, diaphragm design, and connection details. Connections are particularly difficult in adobe buildings because the low strength of the adobe material makes connections likely sources of failure. Connections should be designed such that the local failure of the adobe does not cause complete failure of the material.

Tension anchors are good examples of the type of connection that should *not* be used with a material as weak as adobe. A tension anchor such as that shown in figure 8 should *not* be used in adobe construction. A much more ductile connection can be achieved that avoids the tensile requirements on the adobe material; this can be done by designing the connection to anchor to a horizontal element, such that the adobe material will be compressed. The method shown in figure 9 will create compression on the adobe material and will be extremely unlikely to cause failure, even though there may be some crushing of the local adobe material.

Conclusion

The GSAP research effort at the Getty Conservation Institute was the single largest effort that has yet been made with regard to the study of the seismic behavior of adobe buildings and, more specifically, historic adobe buildings. Aside from just the scope of the effort, the

FIGURE 8 A tension anchor. Such anchors are typically not recommended for adobe buildings.
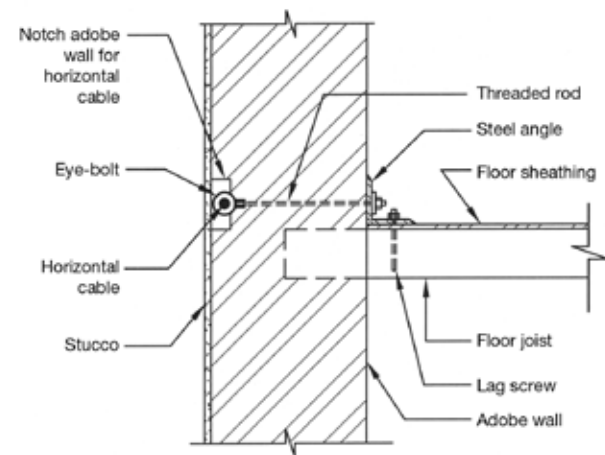

FIGURE 9 Connection between floor framing and a horizontal cabling system. This system will prevent failure due to the poor tensile capacity of the adobe material.

multidisciplinary character of the research also made this work unique in the general efforts with regard to the seismic retrofitting of historic adobe buildings.

But this work could not have been accomplished had earlier research not been conducted around the world—more specifically, in Mexico, Peru, and California. There are continuing efforts to improve the knowledge of adobe structures, and there are clearly research needs with regard to understanding the dynamic behavior of adobe buildings.

Nevertheless, the largest needs for the seismic retrofit of adobe buildings are the application and dissemination of information on a worldwide basis.

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