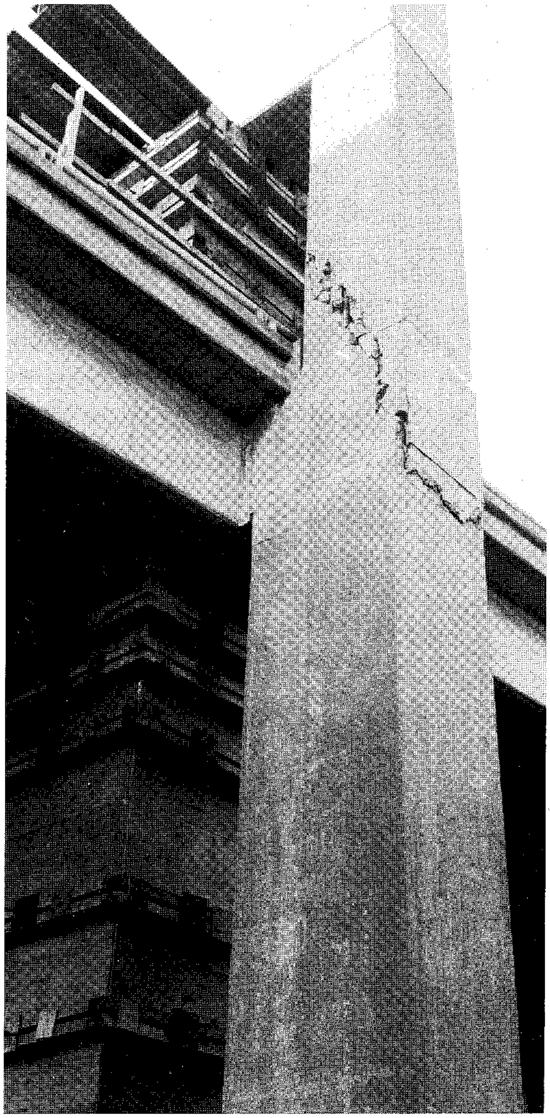
Structural Behavior During the Loma Prieta Earthquake

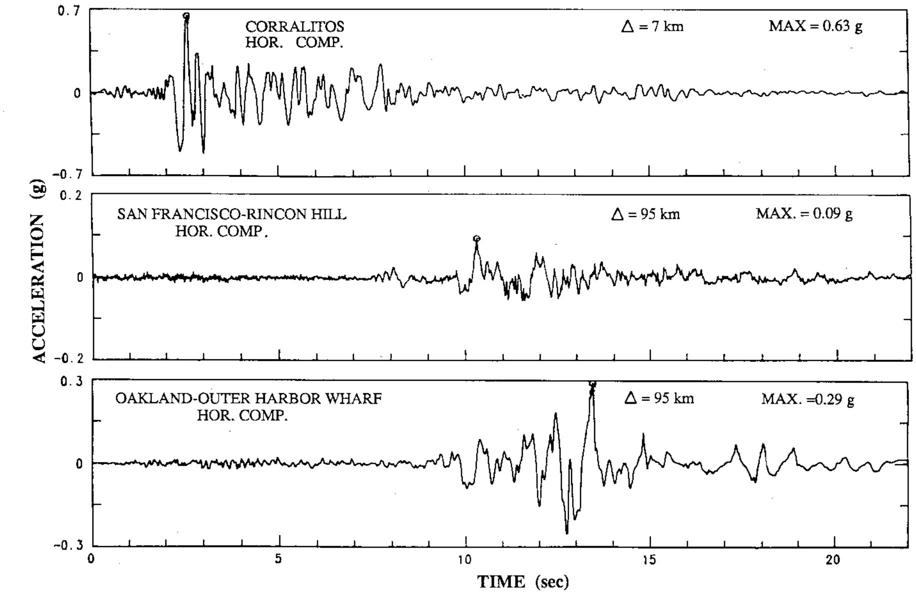
by John F. Hall



The double-deck Embarcadero Freeway, similar to the Cypress Street section of Interstate 880, came perilously close to collapse.

When compared with the magnitude 6.8 Armenian earthquake of December 1988, the Loma Prieta earthquake can be viewed as a demonstration of the success that can be achieved through preparedness and adherence to building codes. In Armenia an estimated 25,000 people died, and whole communities were destroyed. The magnitude 7.1 Loma Prieta earthquake killed 62 persons, and damage was only scattered, with many of the severely damaged structures being older ones built on landfill. Nevertheless, direct losses resulting from the recent earthquake may exceed $10 billion, with damage to more than 100,000 structures. And we must keep in mind that a magnitude 7.1 earthquake is many times smaller than the magnitude 8-plus that the San Andreas is capable of generating when measured in terms of area affected and time duration of strong shaking, important factors in damage potential. Even some of the modern structures that performed well in October 1989 may be vulnerable to a magnitude 8-plus event.

The pictures and discussion that follow present information on the nature of the strong shaking generated by the earthquake and on how some particular and typical structures fared. Emphasis is on those that were built when earthquake effects were poorly understood. Such older structures represent California's most pressing earthquake problem. Source materials for this article include publications by Caltrans, California Division of Mines and Geology (CDMG), Earthquake Engineering Research Institute (EEEI), EQE Engineering, UC Berkeley, and



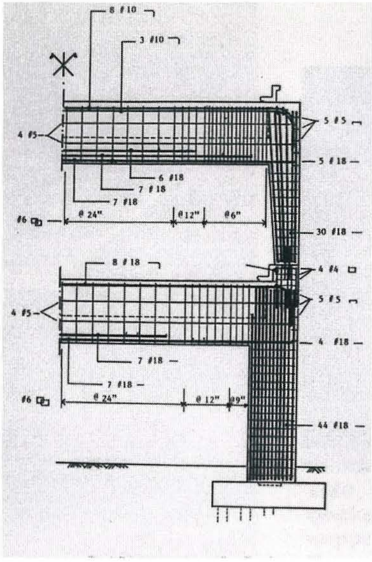
The top accelerogram shows ground motion in terms of acceleration over time at a site 7 kilometers from the epicenter. Comparison of accelerograms from two locations far from the epicenter—on rock in San Francisco (middle) and on mud overlying sand in Oakland (bottom)—illustrates the amplification of ground motion on soft soil.

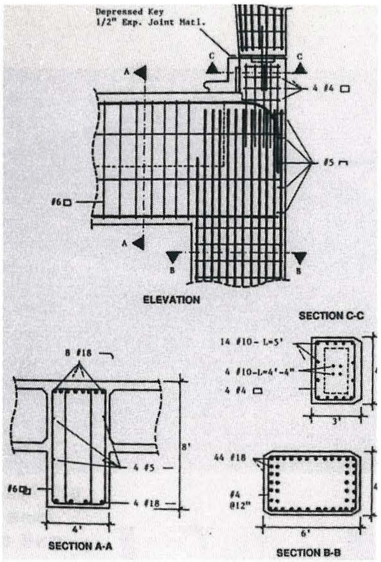
United States Geological Survey (USGS).

A wealth of data was obtained on the nature of the strong shaking generated by the earthquake. These data are records of the motion in terms of acceleration versus time (accelerograms) captured by special vibration recording instruments (accelerographs). Dozens of accelerographs installed over the years by CDMG and USGS triggered during the earthquake. Shown at left are three accelerograms from CDMG; all show a single horizontal component of motion at a particular site on the ground. The Corralitos station was the closest to the epicenter ($\Delta = 7$ km, where Δ = epicentral distance), and there the ground acceleration exceeded 60 percent of gravity with a strong shaking duration of about six seconds. The other two accelerograms were both recorded 95 km from the epicenter, one on rock (in San Francisco on Rincon Hill) with a 0.09 g peak acceleration, and the other on 10 feet of fill and bay mud overlying sand (at Oakland's Outer Harbor Wharf) with a 0.29 g peak acceleration. These two records illustrate the amplification of ground motion that can occur on soft soil. Such amplification probably played an important role in much of the damage that occurred during the earthquake, such as in the Marina District and the South of Market area in San Francisco and at the Cypress Street section of the Nimitz Freeway (Interstate 880) in Oakland. The Oakland Outer Harbor Wharf station was only 2½ km from the collapsed portion of the Cypress, and the motions at these two locations are thought to have been similar.

The Cypress collapse, which accounted for

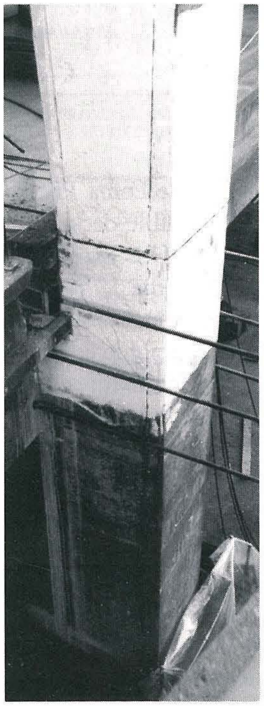
The design of the Cypress Street section of I-880 employed too few wrapping bars around the longitudinal steel reinforcement in the columns as revealed in the original plans (lower-level joint detail at far right; reinforcement layout bent at near right). This led to brittle shear failure at the base of the upper column (below).



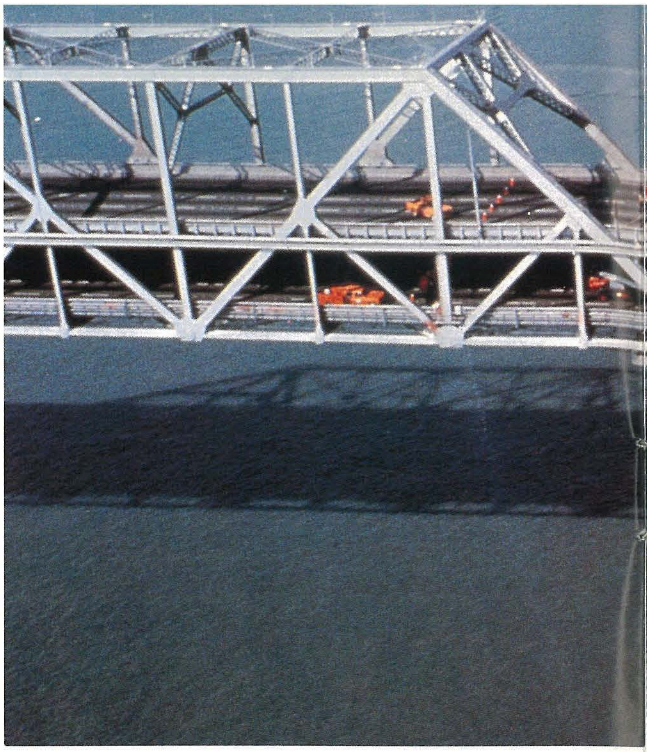


two-thirds of the fatalities from the Loma Prieta earthquake, involved 49 of 85 double-deck spans and extended for 1.2 km. This reinforced concrete structure was designed in the 1950s, before engineers understood very much about earthquake-resistant design using reinforced concrete. In 1971 a number of bridge failures during the San Fernando earthquake led Caltrans to embark on a statewide bridge-retrofit program, the first phase of which involved cabling bridge decks together across expansion joints to prevent the decks from sliding off their joint seats and dropping down during earthquake shaking. The Cypress structure is one of 1,200 bridges statewide that have been so retrofited. Subsequent phases of the state retrofit program deal with column strengthening and are only in their early stages. Many bridges, however, in the area of strong shaking from the Loma Prieta earthquake benefited from the cabling retrofit program.

The drawings above show the pattern of steel reinforcing bars in a typical bent (that is, a frame supporting the decks) of the Cypress structure. The design contains a flaw typical of most older reinforced-concrete structures: an inadequate number of the steel bars, called ties, that wrap around the longitudinal reinforcing bars in the columns. Too few ties make such columns prone to brittle shear failure during earthquakes, which is what happened to the Cypress. The area where the failure initiated is at the base of the upper column, and the failure plane is evident in the photo at left. The deck cabling did nothing to prevent this type of collapse and, in fact, may have helped propagate the failure from one span



Load tests on a surviving section of the Cypress (top) produced the same type of critical shear cracks at the base of an upper column (bottom) that led to the failure of the structure during the earthquake.



to the next by pulling down a bent standing one span away from a collapsed bent. In light of the Cypress experience Caltrans is now reviewing their retrofit program. The future will probably see more complete treatment of important structures with thorough consideration of their entire structural systems.

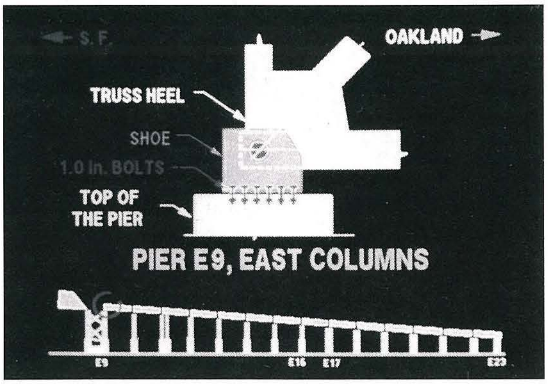
After the earthquake the collapsed and still-standing portions of the Cypress structure were removed except for a two-span, double-deck section south of the part that collapsed. Interestingly, the portion of the Cypress that survived the earthquake was outside the zone of soft soil which underlay the part that collapsed. On the two-span section that was spared demolition, engineers from Caltrans and UC Berkeley recently conducted load tests using jacks placed between the upper deck and massive steel reaction frames, which were installed for this purpose. This type of loading forces the bridge back and forth in much the same manner as it would vibrate during an earthquake, although slower. The test structure was jacked far enough to produce the critical shear cracks at the base of the upper columns (left) confirming this to be the weak point in the design.

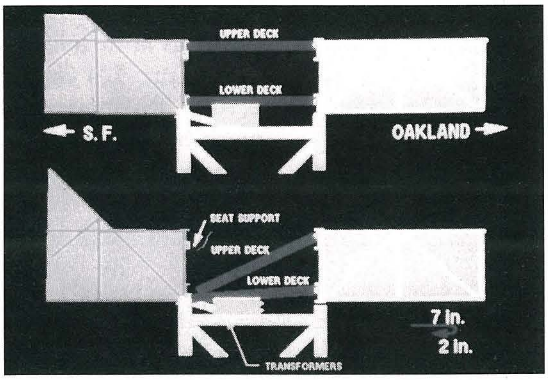
In a later stage of testing, three different methods for strengthening the test structure were tried out. The scheme considered to be the strongest consisted of steel I-sections fastened to the outside of the weakened columns to act as splints. After installation of the trial retrofits, the test structure was reloaded to determine the increase in strength obtained. Caltrans found all three schemes to be effective and plans to use them to retrofit the several freeway structures that remain closed.

A multispan section of the Embarcadero Freeway, a double-deck bridge with similarities to the Cypress structure in Oakland, also came perilously close to collapsing (see photo on page 13). Indeed, the shear cracks in the columns suggest a collapse mechanism similar to that of the Cypress, resulting from a lack of ties in the columns. The Embarcadero remains closed to traffic and is temporarily shored up with timbers, awaiting a more permanent solution, such as retrofiting with the steel splints of the type tested at the Cypress test structure.

In the hours immediately following the earthquake, the most visible symbol of the damage was the collapsed upper and lower roadway decks in the trussed half of the Bay Bridge east of Yerba Buena Island (above). These decks had spanned 50 feet across a massive steel pier (number E9) connecting a 500-foot steel truss on the San Francisco side of the pier with a 300-foot one on the Oakland side. Bolted connections firmly attached these decks to the truss on the Oakland side of the pier, and a 5-inch-wide seat was employed at the end toward San Francisco to permit sliding. During the shaking the forces in the bridge truss on the Oakland side were sufficient to shear the bolts that connected the truss to the pier (top drawing, opposite), after which the truss moved 7 inches on the pier in the direction toward Oakland. This movement caused the decks over the pier, which were bolted to the moving truss at one end, to slide off their seat supports at the opposite end

50-foot upper- and lower-deck spans of the Bay Bridge collapsed across a pier when shaking broke loose one truss to which the decks were attached, resulting in a 7-inch movement toward the Oakland side, which pulled the decks off their seat supports on the San Francisco side.





(bottom drawing). Unfortunately, no cabling retrofit work had been done over pier E9. Similar bolt shearing took place on several other piers closer to the Oakland end of the bridge and, amazingly, the last deck segment came to rest only ½ inch from the edge of its seat without dropping.

The distress suffered by the 55-year-old Bay Bridge from this magnitude 7.1 earthquake 100 km distant has generated concern about the bridge's ability to withstand stronger shaking from maximum earthquakes on the nearby San Andreas and Hayward faults. Caltrans is currently planning for a sophisticated dynamic analysis to be made of the bridge to simulate its response under such conditions. Such an analysis will not be easy because it should account for the numerous sliding joints in the bridge and should consider unsynchronized displacements along the base of the structure as the seismic waves pass by, as well as possible permanent deformation of the foundations.

Damage was sustained by numerous major highway structures, and about half a dozen remain closed. One interesting collapse occurred to the parallel bridges across Struve Slough, a 1964 design, which involved 7 spans on one side and 10 spans on the other. Because of a very weak soil condition consisting of saturated peat, the bridge design employed a pile foundation. To support the bridge decks, the piles were extended upward above the ground and embedded into the undersides of cross beams to which the decks were connected. During the shaking the piles sheared off just below their connection

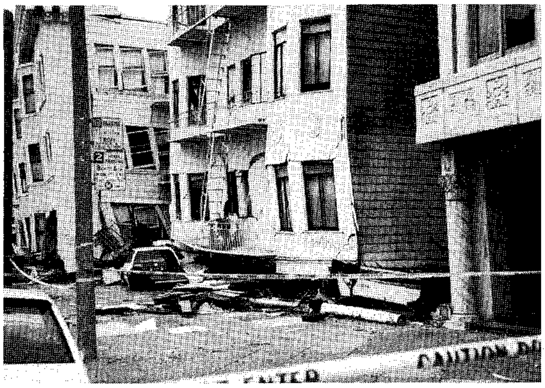
When the parallel bridges across Struve Slough collapsed in weak soil, some of the sheared-off supporting piles punctured the decks as they fell (right). Unreinforced masonry buildings close to the epicenter, such as the one below in the Pacific Garden Mall in Santa Cruz, did not fare well in the earthquake.

with the cross beams, and in a few cases held together enough to puncture cleanly through the deck as it fell, producing a rather eerie sight (above).

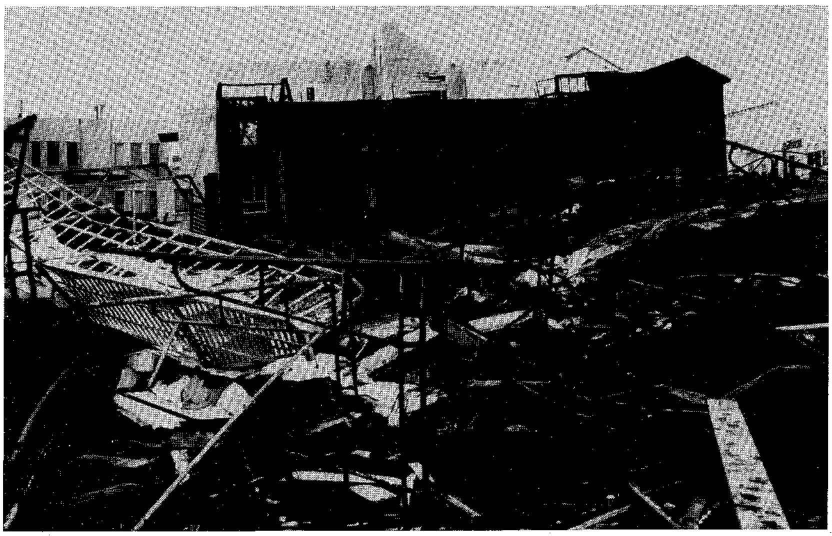
Unreinforced masonry (URM) buildings present a recognized serious hazard to the public during earthquakes. A few cities, such as Los Angeles, have had strengthening programs in effect for several years, and a 1986 California law requires all cities to inventory these old structures and develop mitigation plans by January 1, 1990. The wisdom of such a law was demonstrated by the damage and life-threatening partial collapses suffered by large numbers of URM buildings in the older downtown portions of Santa Cruz, Los Gatos, and Watsonville. The 2,100 URM buildings in San Francisco fared much better; only a few dozen experienced severe damage, with most of these on soft ground in the South of Market area. The majority of San Francisco's URM buildings, located on firm ground or rock, probably saw ground motions on the order of 5 to 10 percent of gravity, not high enough to cause serious damage. But San Francisco, which is still developing its mitigation plan under the 1986 law, should not find solace in the relatively good behavior of its URM buildings. An epicenter closer than the 95-km distance to the Loma Prieta epicenter would have caused much more damage to these brittle structures.

The extensive structural damage in San Francisco's Marina district owed partly to the soil conditions there and partly to the type of construction. Many of the damaged structures were three- to five-story, wood-frame residential buildings dating from the 1920s and contained open first-story parking areas with little bracing (top left). Several of these collapsed in their first story (middle left). The soil in the zone of damage was a loose fill placed in 1915 for the Panama-Pacific Exposition. Evidence from other locations where records of ground motions were obtained indicates that such material amplifies the ground shaking considerably, and this amplification increases the likelihood of damage. The fill material is also prone to liquefaction, and evidence of liquefaction abounded in the Marina. Liquefaction is a type of ground failure and contributed to the structural damage by causing differential settlement of the buildings. Structures similar to those damaged, but located just a few blocks away on firmer ground, sustained little damage.

A fire in the Marina district, an area densely populated with wood-frame structures, proved to be particularly troublesome (aftermath shown in bottom photo). Water was initially delivered to the site from a hydrant in front of the building where the fire ignited (until the building collapsed on the hydrant); then from another nearby hydrant (until breaks in the municipal water system and in a high-pressure auxiliary water system dropped the water pressure); then from the lagoon at the Palace of Fine Arts four blocks away (until other buildings collapsed on the fire hose); and finally from Marina Lagoon via the fireboat *Phoenix*. This effort took about an hour, by which time the fire had spread to other buildings and was shooting flames 75 feet into the air. Control of this fire and more than 20 other smaller ones taxed San Francisco's fire department to its full capacity. Just a few more fires or water-pressure problems might have overwhelmed the local fire-fighting capability right after the earthquake and greatly increased the role of fire in the overall damage. ☐



Damage in San Francisco's Marina district was widespread because of building style, soil conditions, and fire.



John Hall, associate professor of civil engineering, has been a member of the Caltech faculty since 1980, during which time, in addition to the usual faculty duties, he's contributed two other articles to E&S*—on dams and earthquake safety (May 1984) and, with Jim Beck, on engineering features of the Mexican earthquake (January 1986). Currently he's also secretary of the governor's independent board of inquiry into the freeway failures in the recent quake. Hall received his BS from West Virginia University (1972), MS from the University of Illinois (1973), and PhD from UC Berkeley (1980).*