Seismic Retrofit: The California Experience

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RECENT EARTHQUAKES IN URBAN AREAS such as Loma Prieta (1989) and Northridge (1994), California, and Kobe, Japan (1995), have repeatedly demonstrated the vulnerability of transportation systems in general and bridge structures in particular. Bridge failures seem to be the most obvious and most publicized structural deficiencies following a seismic event. Yet little attention is paid to the fact that seismic retrofit technologies developed and implemented during the past 25 years have saved hundreds of bridge structures from severe damage and collapse, and that bridges as a whole, retrofitted with such technologies, represent some of the safest structures with regard to future earthquakes.

Earthquake engineering and seismic design of bridges are comparatively young disciplines. Major developments and advances in these fields have been prompted by seismic events such as those in San Fernando, California (1971) and Loma Prieta. Most bridge construction (85 percent or more)—not just in California, but across the United States and worldwide—predates these events. Thus most structures were designed to no or significantly lower seismic demands than are suggested by current seismic hazard assessments. The result is the need to retrofit a large number of bridges at a very high cost to society, as shown in Table 1 for the State of California alone.

Seismic bridge design was officially introduced in California in 1943 with a static seismic lateral load requirement of 2 to 6 percent of the gravity load. In 1963, bridge design codes were made to conform with Structural Engineers Association of California building code requirements to assess the expected dynamic structural response and lateral load coefficient for the global structure. This approach was inappropriate for bridges, as demonstrated in the 1971 San Fernando earthquake when superstructure unseating at movement joints was identified as one of the major structural deficiencies. Caltrans

Column shear failure was one of several problems experienced by bridges as a result of the Northridge, California, earthquake of 1994.

TABLE 1 Caltrans Seismic Retrofit Program

California Bridge Retrofit Program	Bridge Type	No. of Bridges	Completed or Under Construction	Cost (millions)	Estimated Completion Date[a]
Phase I	Single-Column Bents	1,039	1,035	$813	12/31/98
Phase II	Multi-Column Bents	1,155	1,065	$1,050[b]	12/31/99
Toll Bridges	—	7	2	$2,000[b]	12/31/02
Local Agencies	—	700[b]	100[b]	$200[b]	12/31/98
Total		2,901[c]	2,202	$4,063	

[a] Status as of October 1, 1997.
[b] Estimate.
[c] Represents 12% of the total bridge population of 25,000.

Plastic hinge confinement failures *(above)* and column shear failures *(right)* were among the damage suffered by bridges in the 1971 earthquake in San Fernando, California.

addressed this deficiency through the Phase I retrofit program by installing restrainer cables in bridge movement joints. As a result, with a few exceptions, this type of failure was eliminated in the subsequent Loma Prieta and Northridge earthquakes.

However, the 1971 San Fernando earthquake clearly revealed other bridge deficiencies, such as confinement failures of flexural hinges; reinforcement debonding failures at column ends; and shear failures in shorter, typically multicolumn bents. Between 1971 and 1986, research results and recommendations developed under the Federal Highway Administration-sponsored Applied Technology Council (ATC)-6 program led to significant changes in design practice for new bridges based on the use of acceleration response spectra to determine significantly increased design force levels and detailing requirements for confinement of the column core. The deficiencies in existing bridge columns prompted a Caltrans research program at

Ensuring Safety Against Catastrophic Failures

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The catastrophic collapse of the Silver Bridge in 1967 served as a rude awakening for bridge engineers in the United States. Since then, systematic bridge inventory and inspection programs have been initiated by agencies to evaluate the condition of bridge components. These programs have resulted in repair and rehabilitation activities that have eliminated or reduced condition-related deficiencies that can cause bridges to fail.

Catastrophic bridge failures, however, are not always due to deficiencies in condition. Most structures were not designed in anticipation of today's significantly different design loads and better knowledge of natural events. Design requirements and material characteristics once accepted as the state of the art have been demonstrated with time and further study to be undesirable. Therefore, bridges can be vulnerable to failure modes, such as hydraulic or seismic, unaccounted for in their design.

Current efforts under way in the United States have been addressing the comprehensive safety assurance needed to eliminate or reduce bridge vulnerabilities to catastrophic failure. A nationwide bridge failure survey conducted by the New York State Department of Transportation has identified six failure modes—hydraulic, collision, overloads, steel details, concrete details, and seismic—as most significant.

There are approximately 600,000 highway bridges in the United States, 20,000 in New York State alone, and not all of them are vulnerable to all failure modes. Clearly, for example, bridges not crossing water are not vulnerable to scour failure (hydraulic) or water vessel collision. Therefore, a multilevel vulnerability assessment is used in New York State to screen out from further investigation bridges meeting relevant criteria, and to classify the remaining bridges on the basis of their relative vulnerability (high, medium, or low) to particular failure modes. This process is applied for all failure modes, and provides a uniform measure of the likelihood of failure and its consequences for each structure. The likelihood of failure denotes the probability of external load conditions exceeding structural capacity, whereas the consequences of failure denote the impact in terms of loss of life, injury, traffic disruption, or economic loss. These vulnerability ratings will assist in determining the types of corrective action needed and their urgency. NYSDOT has rated most of its bridges for vulnerability to the hydraulic and steel details failure modes, and has included safety assurance as a component of its bridge management system.

The bridge vulnerability ratings will be used together with condition ratings in determining priorities and making programmatic decisions designed to ensure bridge safety against catastrophic bridge failures.

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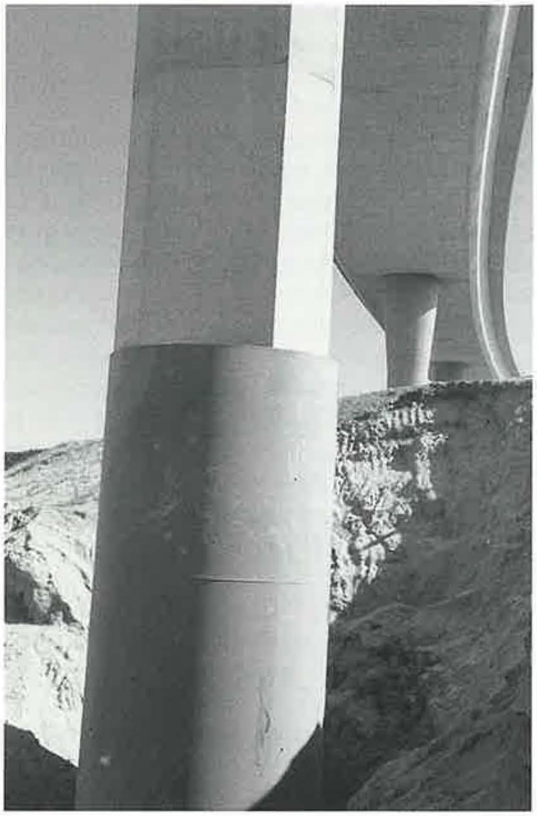
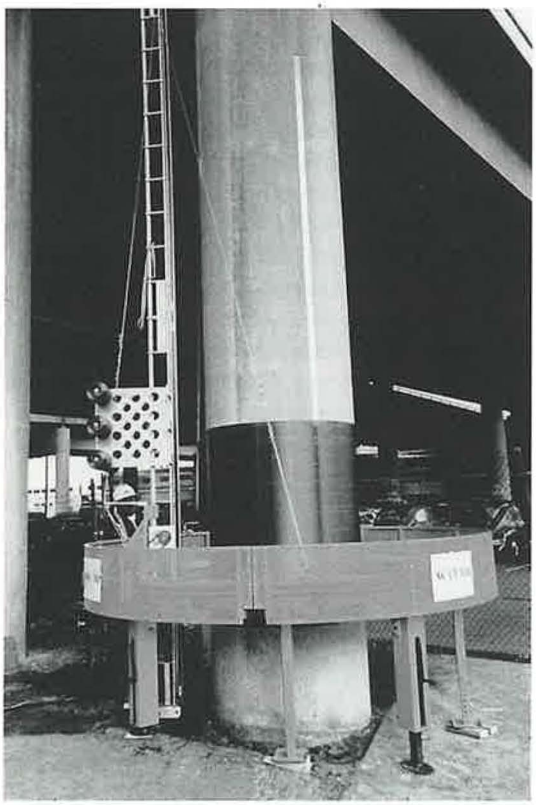
the University of California, San Diego (UCSD) in the mid-1980s that resulted in the now widely used technology of strengthening bridge columns with external jackets.

The timeliness of this research was reemphasized by the Loma Prieta and Northridge earthquakes, which again revealed hinge confinement problems, column shear failure, and bond failures. The 1989 Loma Prieta earthquake resulted in an accelerated retrofit application program in which, as Phase II of the Caltrans bridge retrofit, primarily single-column bents were retrofitted with the UCSD-developed steel jacket technology. Retrofitting of the columns for increased ductility or strength also required that adjacent bridge members be strengthened based on capacity design principles to transfer the increased seismic column forces. For example, spread or pile footings originally built with only a bottom mat of reinforcement require additional piles and top reinforcement to develop the full moment capacity of the column. The success of the Phase II retrofit program became obvious during the 1994 Northridge earthquake. No significant damage to any of the Phase II retrofitted bridges was reported, even though 115 of these bridges were in areas where the ground motions exceeded 0.25 g, and 36 were in areas with ground motion estimates in excess of 0.5 g.

The retrofit technology development and implementation program continued at a rapid pace after the Loma Prieta and Northridge earthquakes. New column jacket technologies utilizing advanced composite (glass and carbon) jacketing systems were developed at UCSD. Numerous tests were con-





The Caltrans bridge seismic retrofit program includes partial-height steel jacketing of single-column bents *(top)* and a recently developed automated advanced composite jacketing system *(below)*.

ducted on joint, cap-beam, and superstructure strengthening at UCSD and various research universities across the United States and worldwide. The seismic design and retrofit concepts thus developed are now widely applied outside of California, modified to meet different seismic hazard scenarios in various regions.

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Strengthening and Rehabilitation Using Carbon Fiber Reinforced Polymer

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In the United States more than 200,000 highway bridges are deficient, many because their load-carrying capacity is inadequate for today's traffic. Strengthening can often be used as a cost-effective alternative to replacement or posting of such bridges.

In 1987 a National Cooperative Highway Research Program study reviewed the methods being used to strengthen various types of bridges; the findings of this study were published in NCHRP Report 293, *Methods of Strengthening Existing Highway Bridges*. The report describes different methods of strengthening, such as providing composite action, reducing dead load, applying external post-tensioning, and modifying load paths.

The strengthening procedure of epoxy bonding steel plates to either steel members or reinforced concrete is mentioned only in an appendix to this report, and there is no mention of the use of carbon fiber reinforced polymer (CFRP) strips. CFRP strips are frequently used today instead of steel plates to restore various bridge elements to their original capacity, or if desired to provide additional capacity. Steel plates have several disadvantages, including susceptibility to corrosion, which necessitates corrosion protection, and heavy weight, which makes handling difficult. Although CFRP strips are expensive, they weigh less, have higher tensile strength, have no corrosion problems, are easier to handle and install, and have excellent fatigue properties.