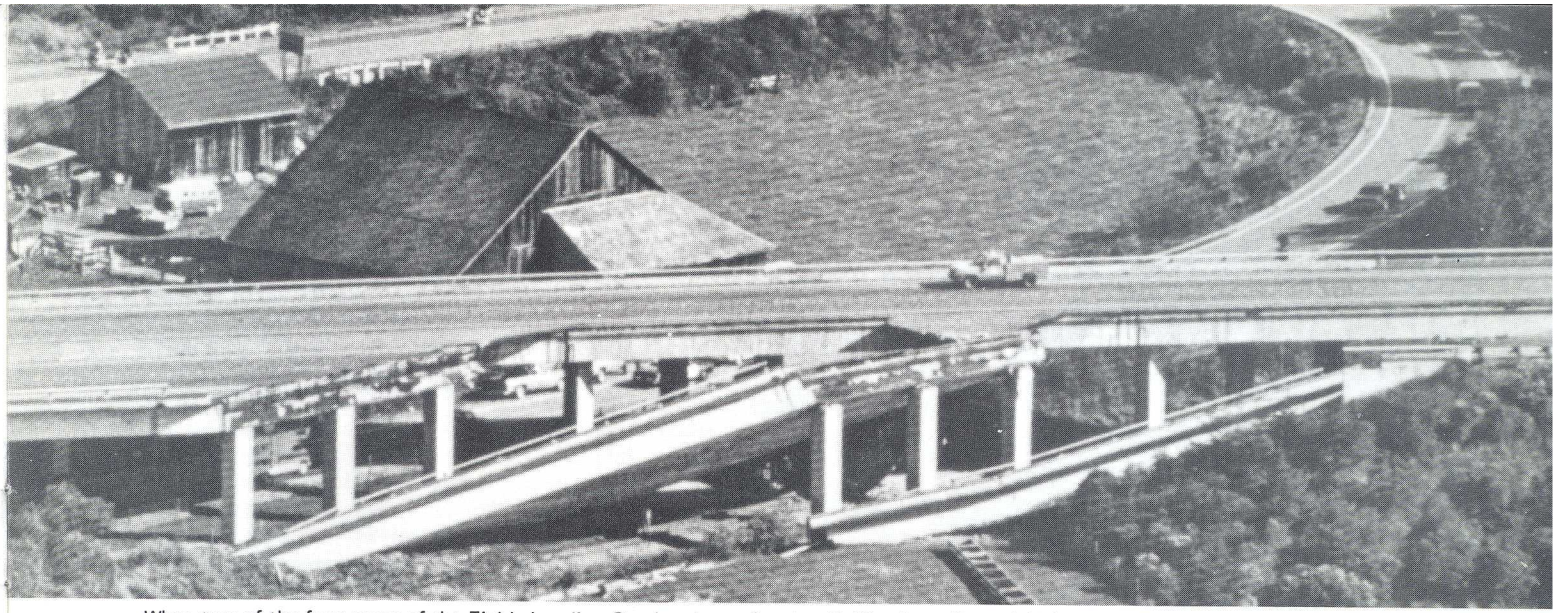

When two of the four spans of the Fields Landing Overhead near Eureka, California, collapsed during an earthquake in November 1980, two automobiles plummeted from the bridge and six persons were injured. In addition to damages and injuries that might result directly from a bridge collapse, disruption of vital transportation lifelines can present an even more serious risk to the community following a severe earthquake. (Photo by Neil F. Gilchrist, Times Standard-Eureka)

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U.S. Department of Transportation
Federal Highway Administration

FHWA R&D Program Produces Major Improvements in Seismic Design of Highway Bridges

JAMES D. COOPER, ROBERT J. REILLY, and BRENDA J. VUMBACO

Late night television occasionally resurrects the Clark Gable movie classic that romanticizes the events surrounding the great San Francisco earthquake of 1906, and viewers can react both to the impact of the film and to the event that set into motion the destruction and reconstruction of that renowned West Coast metropolis. But to residents of earthquake-prone areas throughout the world and to highway engineers and other officials charged with ensuring public safety, the danger associated with this act of nature is fact not fiction, real not imagined. The occurrence of earthquake tremors and related incidents in recent years has prompted a concerted effort to ensure the structural safety of bridges—vital links in the nation's transportation network.

A comprehensive research program coordinated by the Federal Highway Administration (FHWA) has recently achieved its objective of developing and implementing guidelines for improved earthquake protection of new and existing bridges. This program is part of a success story, starting with identification of the need for research and culminating with AASHTO's acceptance of new specification provisions and widespread use by bridge engineers of other important recommendations emanating from the research program.

BACKGROUND

The earth's crust is divided into a number of large plates separated by fault lines. These plates are continually in grinding motion with respect to each other, and earthquakes are produced when a sudden dislocation occurs at some point along a fault. Each year throughout the world about 50,000 earthquakes can be felt without the aid of instrumentation. Approximately 100 of these result in substantial damage. Moreover, because such a wide variety of geological conditions, structures, materials, and other factors are involved, seismic design specialists find it difficult to agree on where and when earthquakes will occur and, most important, their magnitude. Nevertheless, with regard to future major earthquakes in some parts of the United States, one thing that most experts agree on is that the question is not if but when.

Of all natural hazards, earthquakes constitute the greatest threat to life and property. In 1970, some 50,000 people died in one earthquake in Peru; 156,000 people in Japan in 1923; and an estimated 750,000 in a severe earthquake in China in 1976. These disasters occurred in regions less densely populated than many earthquake-prone areas in the United States. Although there is a risk that lives might be lost as a direct result of bridge failures during an earthquake, an even larger concern is that collapsed bridges might cause the region to be cut off from outside help during the disaster, thereby greatly increasing the death toll. Because bridges are essential for crossing both manmade and natural obstacles, it is crucial that they continue to function safely, following an earthquake, when the protection of lives and property depends on the efficient movement of emergency traffic. Bridges exposed to earthquakes must remain acces-

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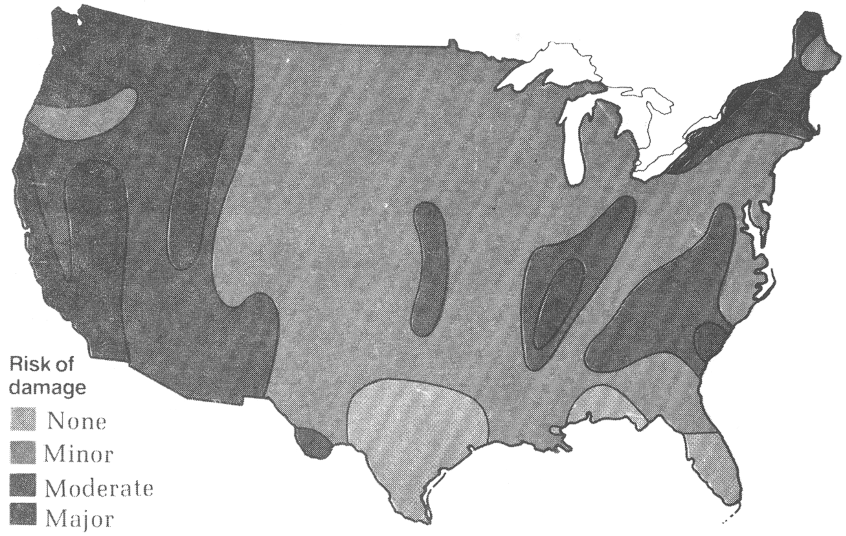


A popular misconception exists that structural engineers need to be concerned with earthquakes only in California and a few surrounding states. But, as this seismic risk map illustrates, the relatively brief recorded history of U.S. seismic activity indicates that more than two-thirds of the states have potential for earthquakes capable of causing serious damage to bridges. More precise (county-level) maps are available with acceleration coefficients for design purposes.

sible and maintain their structural integrity. To aid in this objective, and because seismologists estimate that more than 35 of the nation's 50 states have the potential for ground motions of a ma-gnitude sufficient to cause serious bridge damage, critical areas related to the seismic design of bridges have attracted intense in-terest and are the subject of federal and state-sponsored research studies. Research, especially during the past few years, has cont-ributed to much-improved techniques for consideration of earthquake effects in designing new bridges and retrofitting old ones. Primary among these activities is the FHWA's Earthquake Engineering Research Program, which has recently cap-ped off more than a decade of concentrated effort with the production of comprehensive guidelines for the seismic design of highway bridges.

AN OVERVIEW OF THE PROBLEM

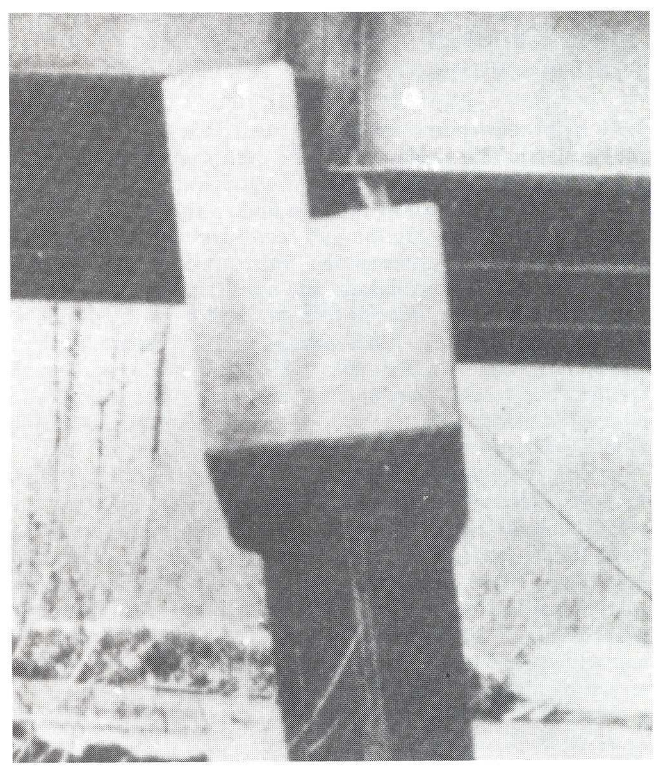
Very little damage to bridges is known to have resulted directly from seismically induced vibrational effects prior to 1971. Most bridge damage on a worldwide basis was caused by permanent ground displacement that had resulted in (a) tilting, settlement, and overturning of substructures; (b) displacement of supports and anchor bolt breakage; and (c) settlement of approach fills and wingwail damage. During the March 1964 Alaskan earthquake, nearly all bridge damage was caused by substructure failures resulting from large ground displacements, settlement, and loss of bearing capacity; substructure failures were also the primary cause of superstructure damage. This pattern was typical of the bridge failures experienced in nine major earthquakes that had occurred in Japan prior to 1971.

In California, which is especially prone to earthquakes, bridge damage of any type was minimal, totaling approximately $100,000 for the 11 most significant earthquakes (Richter magnitude 5.4-7.7) that had occurred from 1933 to 1971. However, the San Fernando earthquake (6.6 magnitude) of February 9, 1971, which took 64 lives, was an important turning point. Approximately $6.5 million in bridge damage occurred and most of it was due to vibrational effects and inadequate connections between structural elements. This event increased public awareness of the potential for earthquake-induced damage to the transportation system and resulted in recognition of the need to design highway bridges that are more resistant to the damaging effects of seismic forces induced by ground motion.

The San Fernando earthquake was the first real "test case" of existing U.S. seismic design provisions for structures in and close to an epicentral region. Modern structures performed well in the regions of moderately strong ground shaking. In regions of very strong ground motion, however, some buildings were severely damaged, and a number of freeway overpass bridges collapsed, resulting in significant local traffic disruption. In a more severe earthquake, such an interruption of transportation services could greatly magnify the disastrous effects. Highway bridges must be designed with adequate safety against collapse under earthquake loading. Herein rest the challenge to bridge engineers and the importance of continued research.

CODES AND SAFETY

A National Academy of Sciences Joint Panel on the San Fernando Earthquake declared in 1971 that "present standard code requirements for earthquake design of highway bridges in high-risk areas are grossly inadequate and should be revised." Until recently, however, almost all considera-



Failures of foundations and substructures are the most common form of bridge distress caused by earthquakes. For example, this bridge pier tilted in the longitudinal direction during the March 1964 Alaska earthquake. Such damage commonly occurs along rivers and results from foundations moving toward the stream bed while the pier tops are restrained by the superstructure.

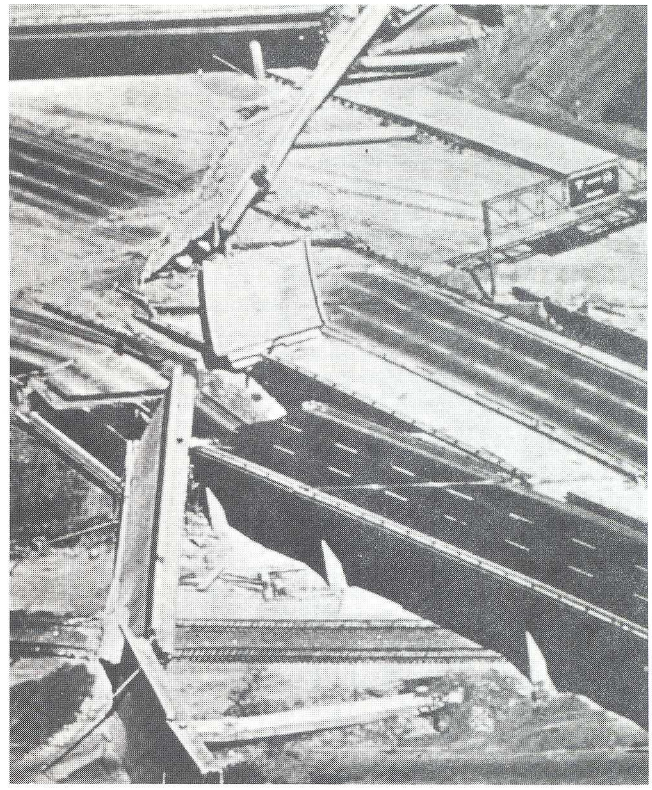
tions of earthquake forces on structures and relevant code provisions have been directed to the area of building construction rather than bridge construction.

The 1925 Santa Barbara earthquake caused several million dollars in damages and gave impetus to the inclusion of seismic design provisions in building codes. The Long Beach earthquake in 1933, with more than $50 million in damages, further demonstrated the need for consideration of earthquake forces. In 1937, the simple Newtonian concept that lateral earthquake force on a structure is proportional to its mass was included in the Uniform Building Code; since then changes have continued in various building codes.

The first provisions in the United States for consideration of seismic loading in the design of highway bridges were included in the *American Association of State Highway Officials (AASHO) 1958 Standard Specifications for Highway Bridges*, and they remained unchanged for more than 15 years. In 1971, new seismic design criteria were being considered for adoption by the AASHO (now AASHTO) Bridge Committee when the San Fernando earthquake occurred and demonstrated that the proposed provisions were inadequate.

The 12th edition (1977) of the *AASHTO Standard Specifications for Highway Bridges* includes a new approach for designing highway bridges to withstand earthquake forces. Article 1.2.20 of the *Specifications* requires that "in regions where earthquakes may be anticipated, structures shall be designed to resist earthquake motions by considering the relationship of the site to active faults, the seismic response of the soils at the site, and the dynamic response characteristics of the total structure." The *Specifications* call for seismic analysis by the equivalent static force method for simple structures and for a more rigorous response-spectra or transient analysis for more complex structures. These provisions are generally based on the 1973 Earthquake Design Criteria for Bridges in the State of California, which were developed for conditions in that state, but were modified to permit application to other areas of the United States. California's design criteria evolved from technical information and code provisions that had been developed primarily for building design but represented the best guidance available for bridges at the time.

A program of research studies, sponsored by FHWA, recently culminated in a comprehensive guide specification that was adopted by AASHTO in 1982 and is already being used as a more rational and consistent approach to earthquake protection of transportation structures.

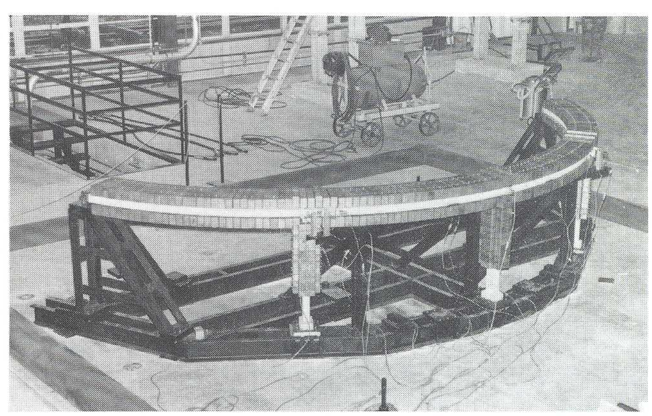


The 1971 San Fernando earthquake dramatically alerted bridge engineers to the need for earthquake protection and was a major turning point in the development of seismic design criteria for bridges in the United States. In a region where much attention has been given to the earthquake hazard, this moderate earthquake directly affected more than 400,000 people by damaging or destroying homes, public facilities, and utilities, at a cost of 64 lives and about $1 billion. More than 100 earthquakes of this magnitude occur around the world each year, but the difference is that this one struck the edge of a large metropolis 136 bridges were severely damaged, and 7 totally destroyed. Shown here are several of the freeway overpass bridges that collapsed during this event; the superstructures were literally shaken from their supports. Following the San Fernando earthquake, FHWA's research program went into high gear to develop improved design standards for new bridges and procedures for upgrading existing bridges.

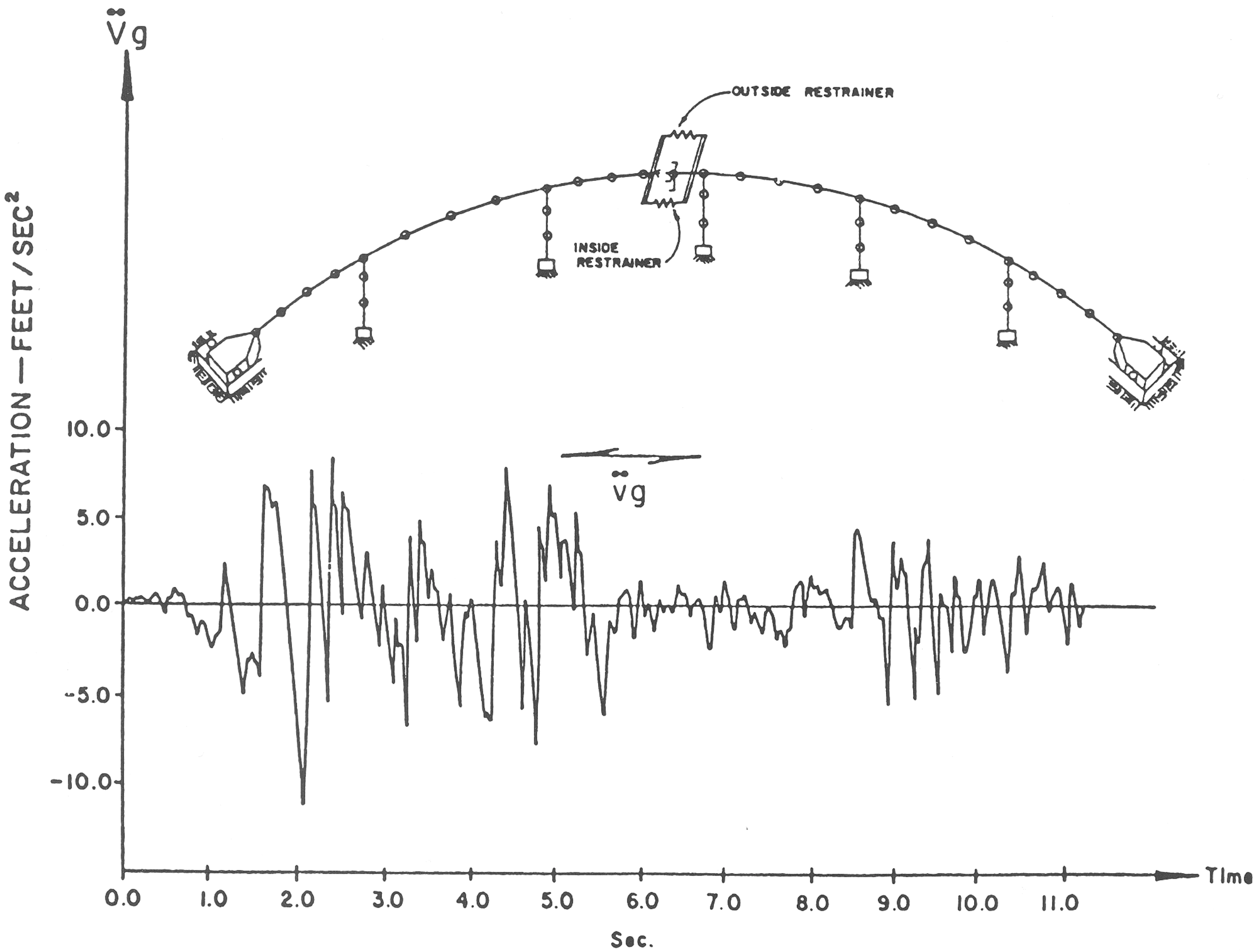
RESEARCH PROGRAM

The FHWA program of earthquake engineering research was initiated in 1969. At first, some internal studies were conducted on the effects of height and distribution of mass in tall piers. When the San Fernando earthquake occurred, FHWA was in the process of negotiating a contract for an initial study by the University of California at Berkeley. However, as a result of the earthquake, the initial work plan was redirected to concentrate on a tall, single-column-supported, curved viaduct that had exhibited disastrous behavior. An increase in the level of funding following the San Fernando earthquake made it possible to expand the program to include other aspects of the seismic design problem and to address the issue of retrofitting existing structures.

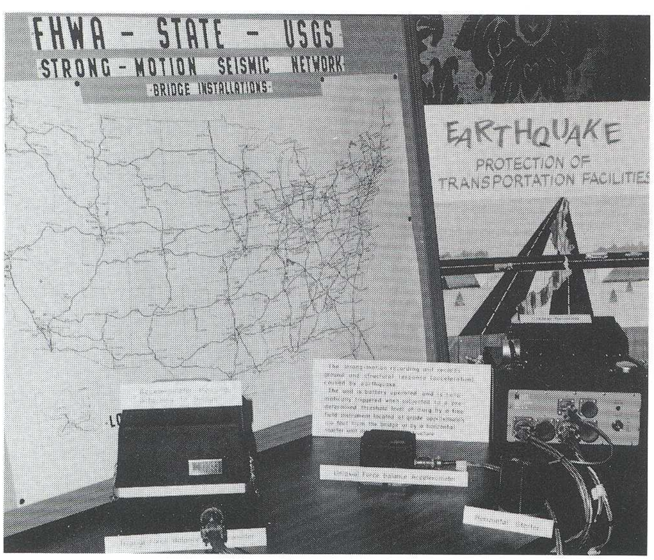
The FHWA mode of managing such a research program combines contract studies conducted by universities, private consultants, or other research organizations; studies supported by federal aid through state highway agencies; projects in the National Cooperative Highway Research Program; and a limited number of in-house studies by FHWA staff. Such work was carried out under Task 1 of Federally Coordinated Program (FCP) Project 5A, "Improved Protection Against Natural Hazards of Earthquake and Wind."



Laboratory experiments are an important part of FHWA's research program. Results help researchers to understand bridge behavior under seismic loading. Shown here is a model of an interchange structur that collapsed during the 1971 San Fernando earthquake. This model was subjected to simulated ground motions on the University of California's shake table and provided useful information on dynamic re-



Mathematical models for dynamic analysis of bridges were developed and put to use in FHWA-sponsored studies. They are used both as research tools and in the design of complex structures. The drawing illustrates a time-history record of ground accelerations applied to a lumped-mass idealization of a six-span curved viaduct. This was part of an investigation of the dynamic response of a bridge that suffered heavy damage during the 1971 San Fernando earthquake.



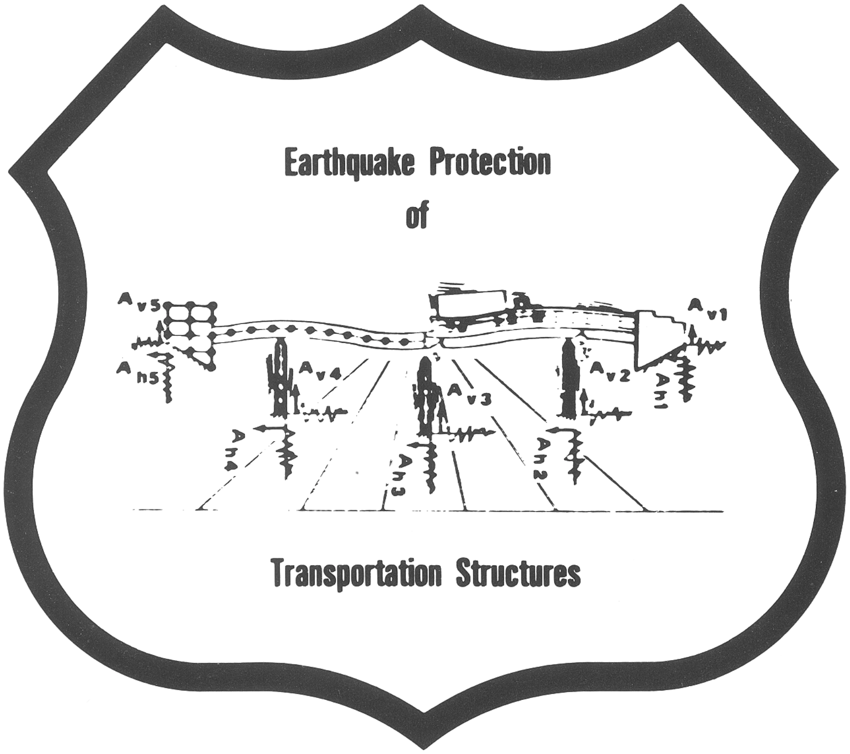
Field measurements of ground motions and structural response during earthquakes provide necessary linkage between the results of laboratory tests, analytical modeling, and actual seismic events. Strong-motion recording units have been installed on bridges in six states as part of a cooperative program involving FHWA, the U.S. Geological Survey, and various state highway agencies.

Early research at the University of California included development of analytical methods, experiments on laboratory models, parametric studies, and evaluation of dynamic response data from bridges under earthquake loading. This basic research laid the foundation for other studies that followed on specific aspects of the problem. Recently, after about 10 years of concerted effort, the program has generated two major achievements of immediate importance to engineers concerned with the protection of bridges against earthquake hazards. Two reports by the Applied Technology Council (ATC), of Palo Alto, California, under contract to FHWA comprise the best guidance currently available on designing new bridges and retrofitting existing bridges.

Other agencies participating in the FHWA Earthquake Engineering Research Program include the California Department of Transportation (Caltrans), the University of Nevada, the Illinois Institute of Technology Research Institute (IITRI), Engineering Computer Corporation, the University of Arizona, the U.S. Geological Survey, and the Earthquake Engineering Research Institute. Also, useful information was obtained from research conducted in other countries, in particular, Japan and New Zealand.

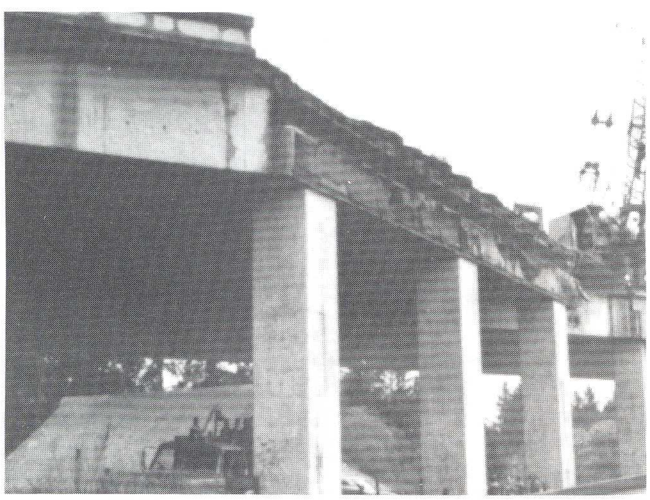
RESEARCH APPLICATIONS

The final reports on the two studies conducted by ATC, in collaboration with a Project Engineering Panel of leading experts, are providing specific guidance needed by bridge engineers.



FHWA's comprehensive research program spanning the 10 years after the 1971 San Fernando earthquake culminated with completion of a major effort to improve seismic design procedures for bridges. The study carried out by the Applied Technology Council, in cooperation with a Project Engineering Panel of recognized experts from industry, academia, state highway agencies, and FHWA, built on the findings of earlier research to develop provisions for design and construction of bridges to minimize their susceptibility to earthquake damage. These design provisions are applicable to all regions of the United States. The guidelines recommended by the researchers, Ronald L. Mayes and Roland L. Sharpe, were unanimously accepted by AASHTO in 1982 and will be published soon as an AASHTO guide specification. The guidelines are comprehensive and embody several new concepts that are significant departures from existing design provisions. They are already being widely used to produce practical designs for earthquake-resistant bridges.

The first report, *Seismic Design Guidelines for Highway Bridges*, was unanimously adopted by the AASHTO Bridge Committee as an AASHTO Guide Specification in 1982. These seismic guidelines contain design and construction requirements applicable to more than 85 percent of the highway bridges to be constructed in the United States. In most cases, all that is required is more attention to structural details that will considerably improve earthquake resistance without significantly adding to the complexity of design or the cost of construction.



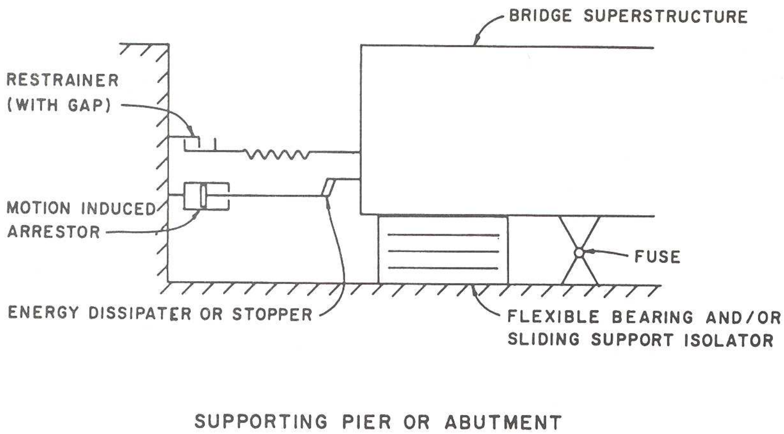
The collapse of two spans of the Fields Landing Overhead during the 1980 earthquake near Eureka, California, vividly illustrates the importance of seemingly minor structural details, such as bearings, joints, and restrainers, in ensuring satisfactory bridge performance in seismically active regions. The collapse occurred because the supports for the bearings were of insufficient length to provide stability under seismic loading. Efficient retrofit procedures are available that could have prevented this bridge from dropping off its supports. At the time of the earthquake, the bridge was scheduled to be upgraded; however, because of the need to budget limited funds among many high-priority needs, the earthquake struck before the retrofit project was initiated.

The earthquake motions and forces specified in these guide specifications are based on an acceptably low probability of their being exceeded during the expected life of a bridge. Bridges and their components that are designed to resist these forces and are constructed using the design details contained in the guidelines may suffer damage, but the probability of collapse due to seismically induced ground shaking will be low. The development of the guidelines was carried out in light of the following basic objectives: minimizing the hazard to life, maintaining the function of essential bridges, not restricting design ingenuity, and ensuring a low probability that design ground motions would be exceeded during the lifetime of the bridge.

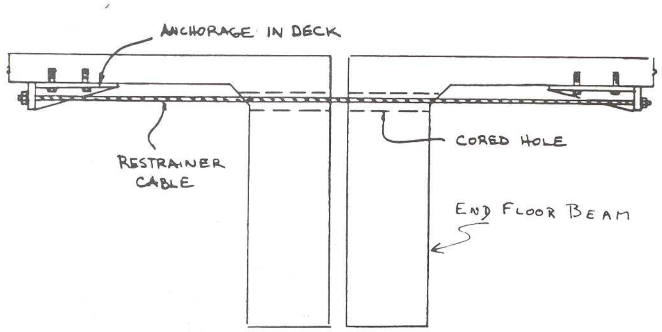
The second report, *Seismic Retrofitting Guidelines for Highway Bridges*, will be published late in 1983 by FHWA. It contains the findings of a study by ATC, building on earlier research by Caltrans and IITRI, and already has helped to create an awareness of relatively simple measures that can be taken to enhance the stability of existing bridges. A systematic approach to identifying and correcting common seismic deficiencies is presented in this report. The recommended concepts are now being used to upgrade existing structures.

CONCLUSION

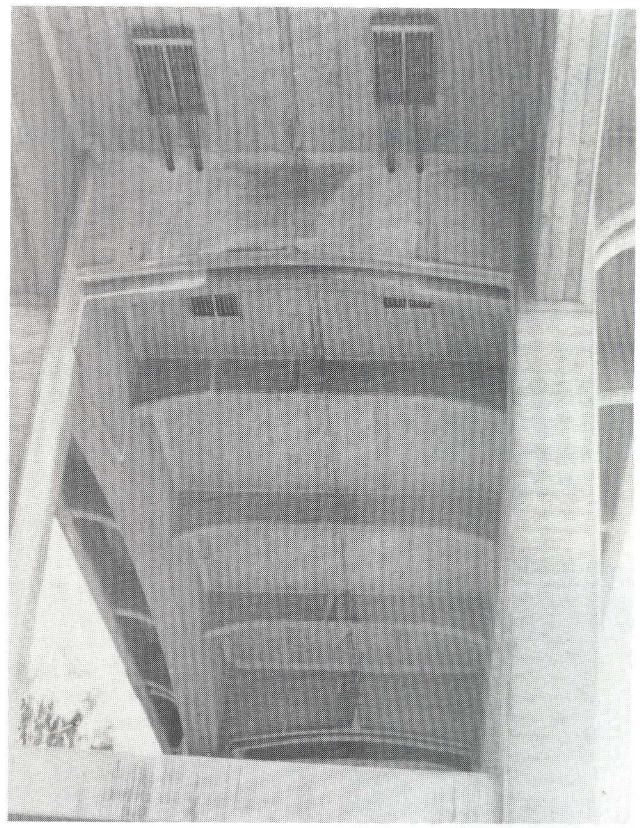
Bridge designers throughout the world are continuing to develop innovative means to make bridges more earthquake resistant. This comprehensive FHWA program has been a vital part of the worldwide effort. The research results have already produced advances in technology through improved guide specifications and through safer, more efficient details for both existing bridges and new construction. While the payoff from the less than $3 million invested in this entire research is not necessarily visible in reduced direct cost, the expected payoff in avoidance of disruption in the transportation network because of earthquake damage and in terms



A generalized concept for an ideal bridge bearing system to resist earthquake motion is shown. In addition to performing all of its functions under normal service conditions, an ideal bearing must also contribute to the overall resisting mechanism of the structure during the seismic event. Following the earthquake, the bearing should facilitate restoration of the structure to its proper alignment and continue to function under service loads. Bearings are now available that incorporate these principles and are being used in new construction and in retrofit programs. Many bearing types found in existing bridges cannot be expected to perform satisfactorily during an earthquake, but retrofit concepts developed in the FHWA-sponsored program make it possible to correct such deficiencies economically as part of an overall bridge rehabilitation program.



Restrainer cables (or bars) tie spans together across an expansion joint and control longitudinal displacements of the superstructure to prevent collapse during an earthquake. This retrofit technique introduces forces that must be accounted for in the columns and foundations. Such restrainers have been used on many bridges in California. (The drawing above shows a longitudinal cross-section through an expansion joint.) Later in 1983, FHWA will publish a report, "Seismic Retrofitting Guidelines for Highway Bridges," containing the best information currently available on upgrading bridges. Concepts presented in this report, prepared by the Applied Technology Council, are already being used, and the concept of improving seismic resistance through relatively simple modification of structural details is gaining widespread acceptance.



of lives saved far outweighs the cost of building better and safer bridges.

The story of FHWA's Earthquake Engineering Research Program is a classic example of the linkage between research and progress in engineering. It started with the recognition of a need for better technology and was followed by a coordinated program of research focused on critical target areas. Fundamental research provided the tools needed for study of important practical problems, and the program was capped by bringing together the best available research and design experience in the form of practical guidelines recommended for immediate application. This story ended happily when application of the recommended design guidelines was ensured by their adoption by AASHTO as a guide specification.

It is not always as easy as it was in this instance to trace the origin of specification provisions, but specifications and codes of practice covering materials, design, and construction are continually being improved, and it is a fact that almost all of these modifications are based on research findings. Modifications to current practice do not always produce monetary savings in terms of lower construction cost. But, as technology continues to advance, engineered construction becomes more cost-effective, durable, and safe; and that is one of the most important dividends from any investment in research.

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