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# The Continuing Challenge: Report on the Performance of State Bridges in the Northridge Earthquake

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Bridges affected by the Northridge earthquake were examined to evaluate the performance of Caltrans bridges, retrofit and peer review programs, and technical procedures. All structures in the region of strong shaking that had been retrofitted since 1989 performed adequately; if the seven bridges that collapsed had been retrofitted, they would be expected to have survived with little damage. The bridges subjected to strong shaking that had been constructed or retrofitted to current Caltrans criteria had, at most, minor damage; all remained in service. The Seismic Advisory Board concluded that the Caltrans seismic design procedures for new bridges and its retrofit procedures for existing hazardous bridges are technically sound. The Board found that the retrofit program is proceeding fairly well, but that the screening methods used to identify hazardous bridges could be improved as could the pace of retrofitting, particularly toll bridges. There were no construction projects underway in the Spring of 1994 for toll bridges, nor had preparation of retrofit designs begun. Twenty-one findings and seventeen recommendations are presented. Although much has been accomplished, much remains to be done. With some improvements, the Caltrans program should be continued with dispatch and determination. The major foreseeable impediments to a successful program are inadequate or fluctuating funding. The Seismic Advisory Board has confidence that the California highway system is progressing in an orderly fashion to one that is significantly more seismically safe.

## 1. OVERVIEW

The Northridge earthquake of January 17, 1994, in the Los Angeles region of California, is the most damaging earthquake to have occurred in California since the 1906 San Francisco earthquake. Northridge had a substantial impact on bridge structures, as had the 1989 Loma Prieta earthquake. Experience in Loma Prieta caused substantial changes in how new bridges are designed and how existing bridges are retrofitted, as well as the retrofit priority setting process for construction. Governor George Deukmejian by Executive Order (D-86-90, June 2, 1990) directed:

> *It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings.*

Caltrans appointed the Seismic Advisory Board (SAB) in September, 1990, as directed by Governor George Deukmejian in Executive Order D-86-90, and in response to recommendations contained in *Competing Against Time: Governor's Board of Inquiry Report on the Loma Prieta Earthquake.* The charge to the Seismic Advisory Board was to provide

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continued, focused evaluations of Caltrans seismic policy and technical procedures. Since that time, the eight-member Board has regularly reviewed Caltrans seismic design, retrofit, and hazard mitigation activities: the Board was composed of George. W. Housner, Chairman, Joseph Penzien, Vice-Chairman, Bruce A. Bolt, Nicholas F. Forell, I. M. Idriss, Joseph P. Nicoletti, Alexander C. Scordelis, and Frieder Seible; Charles Thiel served as editor for their Loma Prieta and Northridge reports.

The Northridge earthquake and its damage to freeway structures provided an opportunity for the Seismic Advisory Board to evaluate the performance of Caltrans bridges, retrofit programs, peer review programs, and technical procedures. The Seismic Advisory Board:

- Evaluated the past four years of changes and developments in seismic design criteria and the highway bridge retrofit program.
- Summarized Board findings on the performance of highway bridges in the Northridge earthquake.
- Recommended improvements to Caltrans bridge seismic design and retrofit programs and procedures.

This paper provides an overview of the SAB's report *The Continuing Challenge* [Housner 1994] and gives its detailed findings and recommendations. The special issue of *Earthquake Spectra,* Northridge Earthquake Reconnaissance Report, Volume 1, provides added technical information on the earthquake and its impacts; Section 6, Highway Bridges and Traffic Management, of this report provides added design characteristics and details of performance, [Earthquake Spectra, 1995]. Caltrans, EERI, EQE and others have also issued reports of observations on this earthquake, [Caltrans 1994, EERI, 1994, EQE, 1994, Moehle, 1994].

## DAMAGE TO HIGHWAY BRIDGES IN THE NORTHRIDGE EARTHQUAKE

Caltrans has approximately 12,000 state highway bridges in California and is responsible for a total of 2,523 state and interstate highway bridges in Los Angeles County. Additionally, about 1,500 bridges are maintained by Los Angeles County and 800 by the City of Los Angeles, and most of these latter bridges are small, single span-bridges and most were remote from the area of strong ground motion. Only a few of the city and county bridges were significantly damaged.

The Northridge earthquake of January 17, 1994 ($M_W$=6.7; $M_W$ is the moment magnitude) caused the collapse of seven highway bridge structures and the consequent disruption of a large portion of the northwest Los Angeles freeway system. Figure 1-1 shows the locations of these bridges in relationship to the earthquake source. Of the seven bridges that collapsed in the earthquake, five had been scheduled as requiring retrofit. Two bridges, the Mission & Gothic Undercrossing and Bull Creek Canyon Channel on State Route 118, had been identified as not requiring retrofit in the first stage. The collapsed structures can be classified by vintage into three groups: three bridges designed and built before the 1971 San Fernando earthquake ($M_W$=6.6); two bridges designed before 1971, but constructed and/or completed after 1971; and, two bridges designed and built a few years after San Fernando, but not to current standards.

Many other bridges in the strongly shaken region sustained damage, but did not collapse. The damage ranged from minor cracking and spalling of concrete to more severe damage that necessitated closing some bridges to traffic while repairs were made.

The bridges in the regions of shaking that were constructed or retrofitted to current Caltrans criteria had, at most, minor damage. All remained in service and none posed a significant safety hazard.

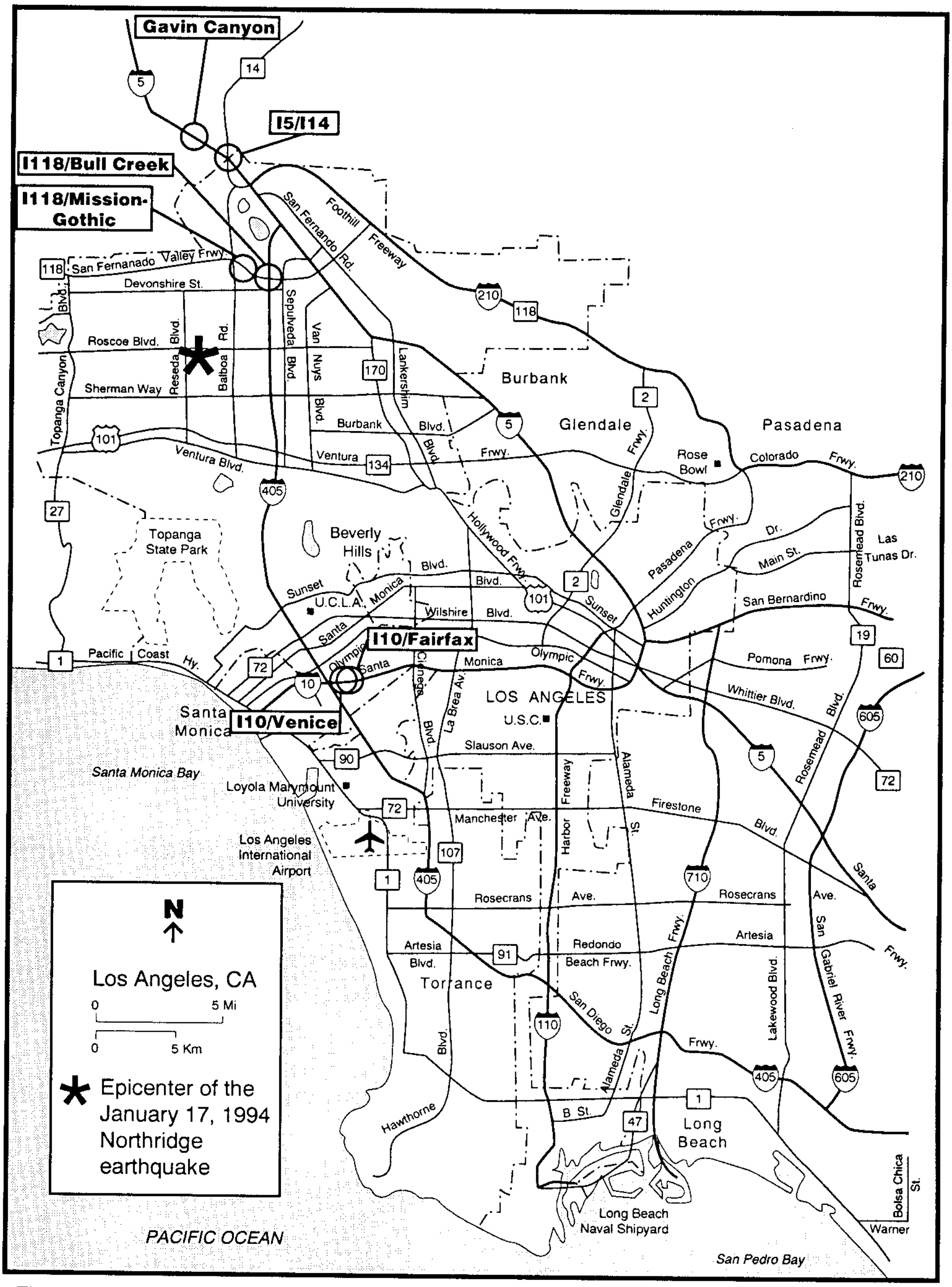


*Figure 1-1. The location of bridges that collapsed in the Northridge earthquake of January 17, 1994; two, the north and south connector overcrossings, collapsed at the I-5/SR-114 interchange.*

*Table 1-1. Caltrans seismic performance criteria and definitions for the design and evaluation of bridges. In the text of this paper the term common is used in place of minimum for all those structures that are designated not important by the definition given below. (Department of Transportation 1994)*

| Ground Motion at the site | Minimum performance level | Important bridge performance level |
|---|---|---|
| Functional evaluation | Immediate service level; repairable damage | Immediate service level; minimal damage |
| Safety evaluation | Limited service level; significant damage | Immediate service level; repairable damage |

*Definitions:*

*Important bridge:* (one of more of the following items present):

- Bridge required to provide secondary life safety (example: access to an emergency facility.)
- Time for restoration of functionality after closure creates a major economic impact.
- Bridge formally designated as critical by a local emergency plan.

*Functional evaluation ground motion:* Probabilistically assessed ground motions that have a 40% probability of occurring during the useful lifetime of the bridge. The determination of this event shall be reviewed by a Caltrans approved consensus group. A separate Functionality Evaluation is required only for Important Bridges. All other bridges are only required to meet specified design requirements to assure Minimum Functionality Performance Level compliance.

*Safety evaluation ground motion:* Up to two methods of defining ground motion may be used:

- Deterministically assessed ground motions from the maximum earthquake as defined by the Division of Mines and Geology Open-File Report 92-1 (1992).
- Probabilistically assessed ground motions with a long return period (approximately 1000-2000 years).

For important bridges both methods shall be given consideration; however, the probabilistic evaluation shall be reviewed by Caltrans approved consensus group. For all other bridges, the motions shall be based only on the deterministic evaluation. In the future, the role of the two methods for other bridges shall be reviewed by a Caltrans approved consensus group.

*Immediate service level:* Full access to normal traffic available almost immediately.

*Repairable damage:* Damage that can be repaired with a minimum risk of losing functionality.

*Limited service level:* Limited access (reduced lanes, light emergency traffic) possible within days. Full service restoration within months.

*Significant damage:* A minimum risk of collapse, but damage that would require closure for repairs.

*Minimal damage:* Essentially elastic performance.

Bridge damage was predictable given the ground motion recorded during the Northridge earthquake. The older bridges were designed for only a small fraction of the ground motion they were subjected to in the Northridge earthquake, and their damage or collapse could be expected. The types of damage observed in the Northridge earthquake are, in the main, consistent with those observed to older bridges in the 1989 Loma Prieta ($M_W$=7.0), 1987 Whittier Narrows ($M_W$=5.9), and 1971 San Fernando ($M_W$=6.6) earthquakes.

## RETROFITTED BRIDGES PERFORMED ADEQUATELY

*All* structures in the region of strong shaking that were retrofitted since 1989 performed adequately, thus demonstrating the validity of the Caltrans retrofit procedures; there were 24 retrofitted bridges in the region of very strong shaking and a total of 60 in the region having peak accelerations of 0.25g or greater. The retrofitted structures resisted the earthquake motions much better than the unretrofitted structures. The Board's conclusion is that if the seven collapsed bridges had been retrofitted, they would have survived the earthquake with little damage.

## CALTRANS SEISMIC DESIGN CRITERIA AND RETROFIT PROGRAM

Caltrans has seismic design performance criteria that set standards for two categories of bridge structures—important and common. Table 1-1 reproduces the Caltrans seismic performance requirements. Important structures are those that do not have convenient alternative routes, whose economic consequences of failure are large, or that provide secondary life safety or are designated as important by local emergency officials. Technical evaluations are made for each type for two levels of earthquake ground motions—the functional and safety levels.

For the safety level evaluation, the Board interpreted the performance statement as explicitly containing the goal that collapse be avoided in earthquakes for all state bridges, whether new or retrofitted. For the functionality level evaluation, Caltrans has adopted performance criteria that will allow post-earthquake damage inspection and repair with minimal traffic interruptions.

Since the 1971 San Fernando earthquake, Caltrans has been engaged in a multi-phase bridge retrofit program . To date most expansion joints have been provided with restrainers or seat extensions and most critical single-column-bent bridges have been retrofitted. Prompted by the 1987 Whittier Narrows earthquake and amplified by the 1991 Loma Prieta earthquake, Caltrans has accelerated the bridge retrofit program and initiated significant changes in bridge design criteria.

### PUBLIC CONCERNS AND QUESTIONS

The Seismic Review Board identified four important questions about the performance of bridges in the Northridge earthquake from those raised by legislators, newspaper reporters, and the public. The questions and Seismic Advisory Board answers are:

1. ***Question:*** Do the results of the Northridge earthquake indicate that the Caltrans seismic retrofit program has been effective and appropriate?

   ***Answer:*** Yes, the technical standards appear sound. All 24 of the retrofitted bridges in the region of intense ground motion (PGA≥0.5g) performed well. It is of some concern to the Board that two of the seven collapsed bridges had not been selected for retrofitting; the other five had been scheduled for retrofit. The screening process used to identify retrofit priorities is evolving and generally sound, but needs improvement. The damage to older bridges was essentially of the same type as observed in California earthquakes during the past 25 years. There was no way to know that the Northridge earthquake could happen before other possible earthquakes that could have occurred at other seismically active sites.

2. ***Question:*** If the bridges that collapsed had been retrofitted before the earthquake, would they have been protected?

   ***Answer:*** Yes. Observed performance indicates that the collapse and major damage suffered by highway bridges in this earthquake would have been prevented if the bridges had been built or retrofitted to current Caltrans criteria.

3. ***Question:*** Is the retrofit program for State of California bridges proceeding at the right pace?

   ***Answer:*** In part. For single-column-bent bridges, nearly all projects are either completed or under construction. For multiple-column-bent bridges, retrofit construction has been completed for only about 7% of the projects. For toll bridges, few design efforts have begun. The number of bridges that have been retrofitted has been controlled primarily by the availability of resources. The pace could be quickened by resolving the administrative, budgetary, contractual and personnel constraints that slow progress.

4. ***Question:*** Do the results of the Northridge earthquake indicate that Caltrans seismic

design procedures for new structures need to be modified?

***Answer:*** No. The Board believes that the current design procedures are appropriate. This earthquake was not a complete test, since longer duration ground motions can be expected in future California earthquakes. Nevertheless, the Board believes that if the heavily-damaged or collapsed structures had been designed to current standards they would have sustained little or no damage. The Caltrans procedures are expected to continue to be improved as new information and observed performance become available.

### JUDGMENTS

The Seismic Advisory Board concludes that the overall performance of Caltrans structures is consistent with the 1990 directives of the Governor and the Legislature on seismic safety of bridges. The Seismic Advisory Board has witnessed fundamental changes in Caltrans policy since the 1989 Loma Prieta earthquake. Immediately following the Loma Prieta earthquake, the Caltrans approach to the replacement and retrofit designs of bridges could be characterized as uncertain at the design level, while management was pushing forward rapidly. In the Spring of 1994, following the Northridge earthquake, both management and design groups seem to be well-synchronized and acting with confidence.

Observations of bridge performance in the Northridge earthquake lead the Board to conclude that the Caltrans seismic design procedures for new bridges and its retrofit procedures for existing hazardous bridges are technically sound. The Board finds that the retrofit program is proceeding fairly well, but that the screening methods used to identify hazardous bridges could be improved. The major issue where substantial improvements can be made is in the pace of retrofitting the existing deficient bridges and particularly the toll bridges. The findings and recommendations of the next section, as well as suggestions in Section 6, provide details on how the Caltrans program can be improved.

Although much has been accomplished, much remains to be done. Earthquakes of similar size to the Northridge earthquake, and even larger, will continue to occur in California. With some improvements, the Caltrans program should be continued with dispatch and determination. The major foreseeable impediments to a successful program are inadequate or fluctuating funding.

The Seismic Advisory Board has confidence that the California highway system is progressing in an orderly fashion to one that is significantly more seismically safe. The Northridge earthquake demonstrates that Caltrans retrofit efforts to date have been responsive to the seismic hazard and the engineering approach of the Department of Transportation is fundamentally sound.

## 2. FINDINGS AND RECOMMENDATIONS

The Seismic Advisory Board bases the following findings and recommendations on its analysis and review of the Northridge earthquake's impacts on transportation structures, the Caltrans retrofit program, Caltrans response to the recommendations contained in *Competing Against Time: The Governor's Board of Inquiry Report on the Loma Prieta Earthquake, May 1990;* directions given by Governor Deukmejian's Executive Order D-86-90, dated June 2, 1990; and to the requirements of Senate Bills 36X and 2104. The basis for these findings and recommendations can be found in the balance of the paper.

The Seismic Advisory Board recommended that the indicated actions be undertaken on a priority basis.

### BRIDGE PERFORMANCE IN THE NORTHRIDGE EARTHQUAKE

1. **Finding:** Caltrans has 12,176 state bridges and of these 9,206 were designed prior to the engineering impact of the 1971 San Fernando earthquake. At this time, knowledge of destructive earthquakes and the seismic performance of structures was in an undeveloped state so that bridges designed prior to the San Fernando earthquake were not up to current standards of seismic design and it was known since the San Fernando, Whittier, and Loma Prieta earthquakes that some of these structures could not survive intense ground shaking. Examples are the Nimitz Freeway double-deck viaduct that collapsed in the 1989 Loma Prieta earthquake and the bridges that collapsed in the Northridge earthquake.

2. **Finding:** Damages observed in the Northridge earthquake are, in the main, consistent with those observed in the 1989 Loma Prieta, 1987 Whittier Narrows, and 1971 San Fernando earthquakes.

3. **Finding:** The Northridge earthquake provided a valuable test for Caltrans design procedures in high-intensity, moderate magnitude earthquakes, but did not constitute a test of their behavior in the larger, long-duration earthquakes that are expected to occur in the future.

4. **Finding:** Of the seven bridges that collapsed, five had been identified and scheduled for seismic retrofit. Two, the Mission & Gothic Undercrossing and the Bull Creek Canyon Channel Undercrossing on State Route 118, had been evaluated as not high-risk and were not scheduled for retrofit.

   **Recommendation:** Caltrans should evaluate those bridges that were not included in the first retrofit group to determine if they require retrofitting. The evaluation should be performed with the essential objective of collapse avoidance in all earthquakes.

5. **Finding:** The performance of recently retrofitted bridges in the Northridge earthquake appears to be acceptable. The evolving post-Loma Prieta earthquake design and retrofitting practices used by Caltrans appear to be sound. No significant damage has been reported to the 60 bridges retrofitted by Caltrans in the region of strong shaking since the start of the post-1987 retrofit program. Prior to 1987, the retrofit approach was to use expansion joint restrainers only. Performance of joint restrainers in the Northridge earthquake was mixed. While retrofitted bridge performance in this event was acceptable, evaluation of the expected performance of these bridges in other earthquakes with greater durations may reveal opportunities for improvement.

   **Recommendation:** A thorough study of the performance of bridges in the Northridge earthquake should be conducted to determine if changes in Caltrans design practices and priority setting procedures are needed. This should be completed through in-house and independent, external studies, as appropriate. Bridges of both concrete and steel should be studied.

6. **Finding:** The public can have confidence in the seismic safety of the Northridge earthquake replacement structures because they are being well designed and peer reviewed.

### RETROFIT PROGRAM

7. **Finding:** Caltrans has made acceptable progress in implementing the retrofit program of single-column-bent bridges, with construction either begun or completed on 100% of identified bridges. In addition to retrofitting the single-column-bents the program includes retrofitting the abutments and footings as needed. For the multiple-column-bents, bridges, the retrofit program has been completed for only about 7% of projects. It has made slower progress on toll bridges, where vulnerability studies are only now being initiated on some, and construction is not underway on any.

**Recommendation:** Caltrans should identify the most hazardous highway bridges in the State and fully retrofit them as quickly as practical, instead of approaching the retrofit programs by category of structures.

**Recommendation:** More emphasis must be given to starting toll bridge retrofit construction projects on as rapid a schedule as practical.

8. **Finding:** The priority setting process used by Caltrans, and as reviewed by the Seismic Advisory Board, involves classifying structures by vulnerability, seismic hazard, and impact on the community. Each category has several elements, some of which do not now appear to be weighted appropriately (for example, soil conditions at the site and the system response of interconnected bridges, such as the sequence of bridges on the Santa Monica Freeway). The present process yields priority lists determined by calculations that do not take into account all important factors affecting seismic safety.

   **Recommendation:** The Caltrans prioritizing procedure should be reviewed and modified based on current understanding. Attention should be given to the quality of information used in the process, including the presence of nonductile columns, variable soil conditions, and the effect that a series of bridges has on the vulnerability of a freeway as an interconnected system. Other characteristics and their weightings should also be re-examined.

## DESIGN

9. **Finding:** Caltrans design procedures have two performance categories: important and common. The performance objective for important bridges is to have full access available to normal traffic almost immediately following a major earthquake. The performance criteria for all common bridges in a major earthquake are to avoid collapse, but to allow significant damage and limited service. While any of three characteristics—secondary safety, economic impact or emergency use—can lead to classification as "important," there is some ambiguity in the specific characteristics that make a bridge important. The public's response to the Northridge earthquake suggests that more bridges should be classified as important than the current procedure yields.

   **Recommendation:** Caltrans should reconsider and broaden the definition of an *important* structure and the appropriate performance objectives for both important and common bridge categories. Concurrently, the acceptance criteria, or limit states, leading to each performance objective should also be defined.

10. **Finding:** The Northridge earthquake occurred on a previously unidentified blind thrust fault, a type of fault that does not have a surface trace. The possibility of blind-thrust earthquakes was well recognized by both the technical community and Caltrans. The Northridge earthquake produced ground motions that were high, but within the range considered possible. With few exceptions, vertical accelerations were not unusually high compared with horizontal accelerations.

    **Recommendation:** Future seismic hazard assessments should consider the likelihood of blind thrust faults.

11. **Finding:** The duration of the strong velocity pulse observed in near field time history recordings during the Northridge earthquake once again affirms its importance to design. It occurs at sites near fault ruptures and above thrust faults. The possibility of a velocity pulse at a site should be given consideration for near field sites in the design of bridges, especially when assessing non-linear response.

    **Recommendation:** The Caltrans bridge design procedures should be assessed, and revised as required, to determine if they adequately reflect the structural demands caused by velocity pulses.

12. **Finding:** The seismic hazard used in the design of common bridges is based only on deterministic evaluations for the maximum earthquakes that can occur throughout the state as prepared by the California Division of Mines and Geology (CDMG). There is some debate as to how these earthquakes and the faults on which they occur should be selected and what attenuation relationship should be used to determine the best estimate of ground motions at a site. The current map only reflects mean peak ground motion estimates; it does not include duration effects or velocity pulses, both of which may be important for common bridge design.

    **Recommendation:** Caltrans should reconsider the technical assumptions leading to the deterministic map and prepare a new one to reflect current understanding of both seismic hazard and the way in which these values are used in bridge design.

13. **Finding:** Caltrans has several hundred steel girder bridges in California. A number of these in the San Fernando Valley area were subjected to strong shaking and sustained severe damage to the end bearings and to the bearing supports. None of these bridges collapsed but at the end of the earthquake they were in a potentially hazardous condition.

    **Recommendation:** Caltrans should investigate the support systems for steel girder bridges and strengthen them as required.

14. **Finding:** Unusual damage was reported to some steel girder bridges. At this writing, two skew bridges have been identified in the region of strong shaking as having cracking in girder webs near welded stiffener plates.

    **Recommendation:** Caltrans should very carefully check all steel bridges and elements in the region of strong shaking to determine if there has been damage. Bridges outside this area throughout the state should be checked for the possibility of having cracks caused by fatigue.

#### CALTRANS MANAGEMENT ACTIONS

15. **Finding:** Caltrans has followed the directions of the Governor based on *Competing Against Time* and the directions of the Governor's Executive Order. Administratively, and in practice, Caltrans is committed to producing seismically safe transportation structures.

    **Recommendation:** Caltrans should continue its commitment to improving the seismic safety of the state's highway bridges.

16. **Finding:** Peer review of the design of new and retrofit bridges has been implemented for complex structures. Peer review is not being conducted for the more prevalent common types.

    **Recommendation:** The scope of projects that are peer reviewed should be extended to include a few representative projects for the more common, prevalent types of structures to validate the design and/or retrofit approach.

17. **Finding:** There is considerable variation in how peer review has been implemented for different structures.

    **Recommendation:** Peer review should be standardized in terms of: 1) which bridges are to be scrutinized; 2) the scheduling of the review to allow designers time to modify the design in response to reviewer comments; and, 3) how complete the peer review should be, ranging from the initial strategy and type selection to the final seismic design detailing. The specific terms of content and format should *not* be standardized—they must be project-specific.

18. **Finding:** Strong motion records were obtained from only six bridges located 14 to 115 miles from the epicenter. None of the bridges that collapsed or had substantial damage were instrumented, thus denying the opportunity to evaluate the effectiveness

of design and analysis procedures by comparison with actual response.

**Recommendation:** Both Caltrans and the California Strong Motion Instrumentation Program must make a greater commitment to installing instruments on bridges, especially toll bridges. Engineers must have recordings from bridges and their sites subjected to high-level ground motions to advance the state of the art in bridge design and analysis.

### STATE ACTION

19. **Finding:** The basic and applied research findings and knowledge that have allowed the development of improved seismic design procedures and practices for bridges have come from research on all types of structure and conditions. The continued development of effective seismic design and retrofit procedures for bridges will depend on knowledge generated in many areas of earthquake engineering.

    **Recommendation:** Caltrans should continue its vigorous program of research and development for bridges.

20. **Finding:** Budgetary, administrative and personnel constraints are the primary reasons why the Caltrans hazardous-bridge retrofit program had not accomplished as much as desirable prior to the Northridge earthquake. In the past, limitations on budget and personnel were the principal drawbacks. Now the issues are: 1) the number of people assigned and their skill levels; 2) the ability of management to contract with qualified engineers to develop designs; and, 3) the ability to initiate construction contracts. Caltrans is working near the limit of what can be realistically done with their current personnel levels and procurement limitations.

    **Recommendation:** If the public wants safer bridges faster than at the current pace, then it will have to provide greater resources, including both administrative and personnel needs, and resolve the legislative, legal, and administrative impediments to implementing retrofit projects quickly.

21. **Finding:** The two collapsed bridges on the Santa Monica Freeway (I-10) were removed, new spans were constructed, and normal traffic flow was established by May 20. This rapid replacement of the damaged bridges was accomplished by means of special contractual arrangements that provided incentives for completion ahead of schedule and disincentives for completion behind schedule.

### CONCLUSIONS

The Seismic Advisory Board concluded that the public should have confidence that new and recently retrofitted structures are being designed and constructed to incorporate current knowledge. The public should have confidence that Caltrans is working diligently and with deliberate speed to retrofit hazardous bridges. On the basis of observations in the Northridge earthquake, the seismic vulnerability of California's highway structures is significantly decreasing with time.

## 3. THE NORTHRIDGE EARTHQUAKE AND BRIDGE PERFORMANCE

### THE NORTHRIDGE EARTHQUAKE

The Northridge earthquake of January, 17 1994, strongly affected the northern parts of Los Angeles and the San Fernando Valley and surrounding areas in southern California. It was the most costly single natural disaster in the history of the United States. This magnitude 6.7 earthquake occurred at 4:31 am local time on a Monday, and resulted in about 65 deaths and over 5,000 casualties. Preliminary damage estimates are in the range of $15-30 billion, [ES, 1995].

The earthquake occurred in a highly-populated, urban area. Most affected structures were built in this century. The earthquake caused serious damage and failures in commercial and residential buildings, destruction of the contents of many structures, damage to critical transportation systems, and widespread disruption of utilities and other lifelines. Of great public concern was the collapse or partial collapse of seven bridges of the freeway system (Figure 1-1). In part because of the time of occurrence, only one life was lost from these bridge collapses.

The 1994 Northridge earthquake was in an urban area containing structures of many types. It provided a first test for many modern seismic design practices. Many of these appear to have been very successful, but some now appear to be questionable. The damage to steel bridges and recently completed steel-braced and welded moment frame buildings was unexpected, [SAC, 1995]. Recently-constructed bridges and post-1987 retrofitted reinforced concrete bridges, on the other hand performed satisfactorily, as expected.

## SEISMOLOGICAL CHARACTERISTICS AND GROUND MOTION

The January 17, 1994, main shock of the Northridge earthquake was generated beneath the San Fernando Valley near Northridge at a focal depth of about 18 km. It occurred on a blind thrust fault, i.e., the principal rupture did not break the surface. Figure 3-1 shows the distribution of Modified Mercalli Intensities (MMI), giving a sense for the shaken areas. It is of interest that within intensity VII zone, pockets of intensity VIII are mapped south of the Santa Monica Mountains.

Since the 1987 Whittier Narrows earthquake, the occurrence of blind-thrust fault earthquakes through the Los Angeles and San Fernando Valleys has been widely accepted, with the likelihood of earthquakes of magnitudes about 6.5 generated by slip on them. In this sense, the type of faulting which produced the Northridge earthquake was not unexpected. The exact position of the causative fault, however, was not predicted. The intensity of shaking appeared to be systematically somewhat higher than expected, based on average attenuation curves for past California earthquakes. Nevertheless, the majority of ground motions fell within the 84% expectation levels (mean plus one standard deviation) and would thus be accommodated by present probabilistic methods of seismic motion assessment. Apart from a few anomalous sites, contrary to some public impressions, the measured peak vertical accelerations (as compared with the observed horizontal values) were also in the expected range of values.

Numerous strong motion instruments had been placed by the California Strong Motion Instrumentation Program (CSMIP) and the U.S. Geological Survey. One-hundred and thirty-two instruments within a 100-mile radius of the fault rupture area recorded the free-field, strong ground motions [Shakal et al, 1994; Porcella, 1994]. These records show that:

- Duration of strong motion was about 9 seconds.
- With few exceptions, peak ground motions recorded were within the statistical ranges expected for such an earthquake.
- Ratios of vertical to horizontal peak ground accelerations were typical of past earthquakes, averaging about 2/3.

Strong motion records were obtained from six bridges at distances ranging from 14 to 115 miles. The most significant of these was the record from the I-10/I-405 Interchange, a curved concrete box girder structure, 1,037 feet long having nine single-column bents and two open-seated abutments. The bridge was retrofitted in 1991 with steel jackets on some columns. Installation of instruments was completed, funded by Caltrans, just before the earthquake. A peak acceleration of 1.83g was recorded at the box girder near the west abutment. This bridge

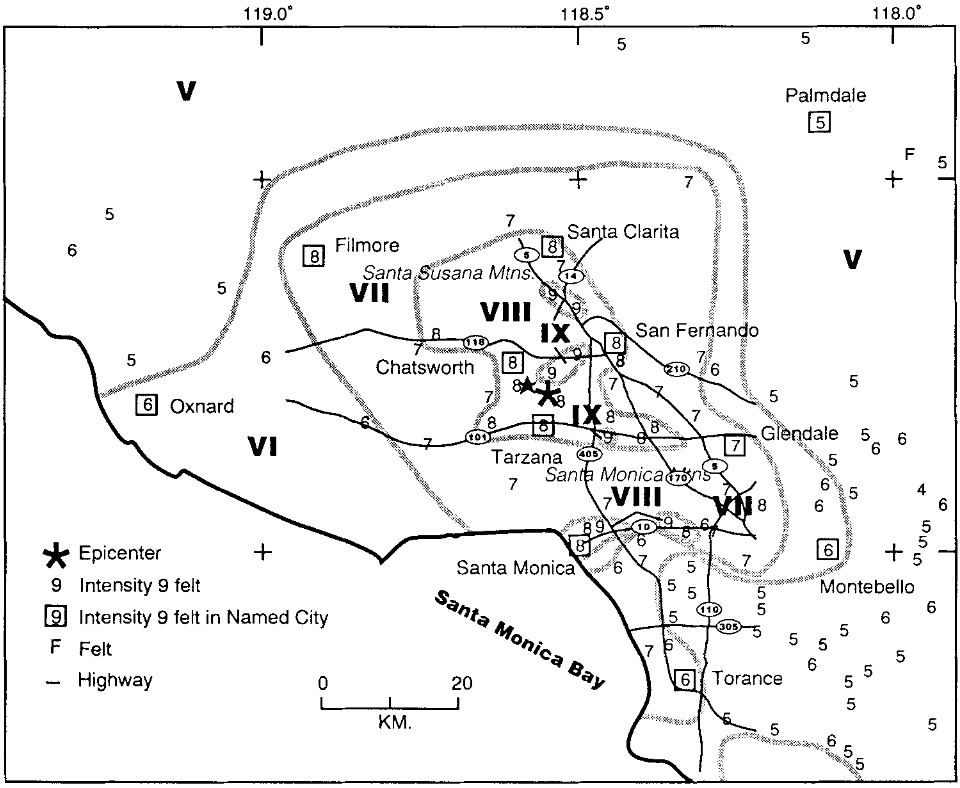


*Figure 3-1. Isoseismal map of the Modified Mercalli Intensities for the Northridge earthquake. The locations of principal highways are indicated for the region of strong shaking. (Porcella, 1994)*

is located about 4 miles west of the section of the I-10 Freeway that collapsed.

### SUMMARY OF DAMAGE TO HIGHWAY BRIDGES IN THE NORTHRIDGE EARTHQUAKE

Caltrans is responsible for a total of 2,523 state or interstate highway bridges in Los Angeles County. Additionally, about 1,500 bridges are maintained by Los Angeles County and 800 by the City of Los Angeles. Only a few of the City and County bridges were significantly damaged. Most of these latter bridges are small, single span bridges and most were remote from the area of strong ground motion.

The Northridge earthquake of January 17, 1994 caused the collapse of seven highway bridge structures (Figure 3-1) and the disruption of a large portion of the northwest Los Angeles freeway system. The collapsed structures can be classified by vintage into three groups: bridges designed and built before the 1971, San Fernando earthquake; bridges designed before 1971 but constructed shortly after 1971; and, bridges designed and built a few years after San Fernando, but not to current standards.

Bridge damage was predictable given the ground motions recorded during the Northridge earthquake. The older bridges were designed for only a small fraction of the ground motions they were subjected to in this earthquake, and their damage or collapse was inevitable. The many bridges in the regions of strong shaking that were constructed or retrofitted to current

*Table 3-1. Summary of highway bridge collapses in the Northridge earthquake.*

| Bridge | Route | Bridge number | Design | Construction completion | Restrainer retrofit | Probable cause of collapse |
|---|---|---|---|---|---|---|
| Gavin Canyon Undercrossing | I-5 | 53-1797 P/L | 1964 | 1965 | 1974 | Skew geometry and unseating of expansion joints |
| N. Connector Overcrossing | SR-14/I-5 | 53-1964 F | 1968 | 1974 | 1974 | Short column brittle shear failure |
| S. Connector and Overcrossing | SR-14/I-5 | 53-1960 F | 1968 | 1974 | 1974 | Short column shear failure |
| Mission & Gothic Undercrossing | SR-118 | 53-2205 | 1973 | 1976 | — | Flexure/shear failure in architectural flared columns at bottom of flare |
| Bull Creek Canyon Channel Undercrossing | SR-118 | 53-2206 | 1973 | 1976 | — | Flexure/shear failure in shortened columns by channel wall and low transverse reinforcement ratio |
| Fairfax & Washington Undercrossing | I-10 | 53-1580 | 1962 | 1964 | 1974 | Flexure/shear failure of short and stiff columns |
| La Cienega & Venice Undercrossing | I-10 | 53-1609 | 1962 | 1964 | 1978 | Brittle shear failure of stiff columns |

Caltrans criteria had, at most, minor damage; and all remained in service and none posed an increased safety threat during the earthquake.

Table 3-1 lists the seven major bridges that collapsed during the Northridge earthquake, along with the date of their design and construction and the probable cause of failure. All seven were constructed to design standards that were much less stringent than those Caltrans currently uses. Section 4 discusses in detail how the bridges performed and current thinking as to why they failed.

Many other bridges in the strongly shaken region sustained damage, but did not collapse and remained in service, either full or limited. The damage ranged from minor cracking and spalling of concrete to more severe damage that necessitated closing the bridge to traffic while repairs were made.

### IMPACT ON TRAFFIC FLOW IN LOS ANGELES COUNTY

Immediately following the Northridge earthquake, Caltrans moved quickly to mobilize construction equipment and personnel to remove debris and restore or reroute traffic where damage had occurred to the highway system.

The failure of the bridges listed in Table 3-1 caused substantial rerouting of traffic. Table 3-2 identifies the damaged state highways in the county and their average daily traffic volumes before the earthquake and on February 4, 18 days after the earthquake. Traffic records for each of 10 days preceding February 4, show that the average delay on each route decreased as alternate routes were opened and drivers became accustomed to changed highway conditions. As of February 4, 1994, the delays ranged from 2 to 25 minutes, significantly less than the initial delay times, which had been as much as 2 hours immediately following the earthquake.

*Table 3-2. Comparison of the average daily traffic volumes on the damaged highways before the Northridge earthquake with the corresponding daily traffic volumes on February 4, 1994. The percentage is the ratio of current daily traffic volume to the average level in January before the earthquake.*

| Route | Location | No. of Lanes | Normal | Pre EQ Jan. Avg. | 2/4/94 | Percent |
|---|---|---|---|---|---|---|
| 5 | South of Rte 170 | 8 | 151,000 | 156,880 | 149,663 | 95% |
| 10 | East of Rte 405 | 8 | 267,000 | 267,273 | 113,029 | 42% |
| 101 | West of Rte 405 | 10 | 275,000 | 309,049 | 267,371 | 87% |
| 105 | East of Rte 405 | 8 | N/A | 171,135 | 186,234 | 109% |
| 118 | West of Rte 405 | 8 | 139,000 | 125,279 | 48,532 | 39% |
| 134 | East of 101/170 IC | 8 | 200,000 | 197,973 | 264,909 | 134% |
| 170 | North of Rte 101-SE only | 4 | 177,000 | 78,058 | 76,143 | 98% |
| 405 | North of Rte 10 | 10 | 274,000 | 271,940 | 234,834 | 86% |
| 405 | South of Rte 10 | 10 | 316,000 | 321,694 | 298,851 | 93% |

## PERFORMANCE OF NEW AND RETROFITTED BRIDGES IN THE NORTHRIDGE EARTHQUAKE

No significant damage has been reported to bridges constructed or retrofitted since the 1987 retrofit program began. Two bridges on State Highway 118 (Mission-Gothic and Bull Creek Canyon) that suffered partial collapse during the Northridge earthquake were designed in 1973, but with criteria that did not reflect current performance criteria. These bridges were on the thrust block over the fault slip and were subjected to very strong ground motion.

Most of the remaining bridges that experienced total or partial collapse, as well as other bridges with major damage, were constructed before 1971 and had not been retrofitted. Several of the bridges that suffered major damage (i.e., State Route 14/I-5 Interchange) had been previously damaged or completed with essentially the same design and using the original piers and footings; one replacement pier and one new pier were designed and constructed with spiral reinforcement.

Loss of support at superstructure hinges was a prevalent cause of distress in the 1971 earthquake, [Jennings, 1971]. The hinge restrainers and seat extenders installed after that earthquake apparently functioned satisfactorily during the Northridge earthquake. Although damage to hinge restrainers, diaphragm anchorages, or bearing seats occurred at 46 separate locations, partial superstructure collapse due to failure of the restrainers occurred only on Route I-5 over Gavin Canyon, where the highly skewed joints and ineffective placement of the restrainers contributed to the loss of support and partial collapse.

The above observations, as well as detailed performance assessments (Priestley, Seible and Uang, 1994) indicate that collapse and major damage to bridges by this earthquake could have been precluded if the bridges had been built or retrofitted to current Caltrans criteria.

## PERFORMANCE OF STEEL STRUCTURES

Caltrans has several hundred steel girder bridges in the State Highway System. Approximately 125 steel girder bridges are located in the Greater Los Angeles area and some of these were in the strongly shaken region during the Northridge earthquake. These bridges had all been designed prior to the San Fernando earthquake and as a consequence of the intense ground shaking that they experienced, some sustained significant damage to the end bearings and to the structure supporting the bearings. None of the damaged bridges collapsed but some were in a potentially hazardous condition at the end of the earthquake. It is clear that the weaknesses were a consequence of underestimating the magnitude of the seismic forces that could be developed during an earthquake.

In addition to the damage to the bearings and the supports, several steel girder bridges sustained damage to the web-plate of a girder near stiffeners. Two skew bridges in the region of very strong shaking have been identified as having such cracks. It appears that some cracks were initiated during the earthquake, and others were there before the earthquake but were extended during the shaking. The worst cracking has already been repaired by grinding out the cracks and rewelding, (Astaneh, 1994).

## 4. WHY DID HIGHWAY BRIDGES COLLAPSE IN THE NORTHRIDGE EARTHQUAKE?

Seven highway bridge structures collapsed during the Northridge earthquake (see Table 3-1 in Section 3 for locations). These seven can be classified by vintage into three groups:

1. Bridges designed and built before the 1971 San Fernando earthquake (Gavin Canyon Undercrossing on I-5, the Fairfax & Washington Undercrossing on I-10, and the La Cienega and Venice Undercrossing on the I-10 Santa Monica Freeway).
2. Bridges designed before 1971 but constructed and/or completed after 1971 (I-5/SR-14 Antelope Valley Interchange).
3. Bridges designed and built after 1971, but before basic design concepts were changed in 1974 (SR-118 Simi Valley-San Fernando Freeway at Mission & Gothic and Bull Creek Canyon).

This section presents preliminary findings on why these bridges performed as they did. Later research and evaluation efforts should examine bridges that did not fail, so that the differences in performance can be understood and their implications for design codified.

### BRIDGES DESIGNED AND BUILT BEFORE THE 1971 SAN FERNANDO EARTHQUAKE

About 76% of the California's highway bridges were built before 1973, the date when modern seismic bridge design practices were introduced that incorporated the lessons of bridge performance in the San Fernando earthquake. Of the 12,176 state bridges, 9,206, or 76%, were built before 1973; of the 11,976 state bridges, 9,170, or 77%, were built before 1973.

Three bridge structures that were completed before, and survived, the 1971 San Fernando earthquake were the Gavin Canyon Undercrossing on I-5 and the Fairfax & Washington Undercrossing and the La Cienega & Venice Undercrossing on the I-10 Santa Monica Freeway. In the 1960s, when these bridge structures were designed and built, earthquake engineering in general was not very advanced. This is reflected in seismic bridge design guidelines of that period that required elastic lateral load designs typically for only 6 percent of gravity, about one-third of today's requirement, without any provisions or considerations for inelastic structural response and ductile design detailing. Key characteristics inherent in these pre-1971 bridge structures are

1. Low transverse reinforcement ratios in columns , typically #4 @ 12" (1/2" diameter reinforcing bars at 12-inch centers) were provided nominally, without consideration of column size or strength.
2. Short seat width at abutments and superstructure expansion joints due to underestimated displacement demands, as a result of the low lateral design loads.

The collapse at the I-5 Gavin Canyon Undercrossing can be attributed to geometric complexities arising from the 66-degree skew orientation of abutments and in-span expansion joints, as well as the 8-inch seat width. Even though retrofitted with first generation restrainers in 1974 (as a direct result of the 1971 San Fernando earthquake), restrainer design and detailing were not sufficient to prevent unseating and subsequent superstructure failure in the acute corners of the bridge at the in-span expansion joints.

Since the restrainer retrofit in 1974, continued research and development of restrainer units funded by Caltrans [Selna, Malvar, and Zelinski, 1989], as well as a better understanding of the skew geometry problems under seismic loads [Priestley and Seible, 1991], would result now in significantly larger seat width extensions and restrainer capacities. However, quantitative failure assessments immediately following the Northridge earthquake [Priestley, Seible and Uang, 1994] also indicate that shear failure in the shorter bents at the Gavin Canyon Undercrossing was imminent, had unseating and superstructure failure not occurred.

Pre-1971 transverse reinforcement detailing in columns was also a problem due to the low transverse reinforcement (nominal #4 @ 12") for the two bridge collapses at the I-10 Santa Monica Freeway. As stated above, the state of the art in bridge design at the time provided transverse column reinforcement only nominally, and not as a result of engineered capacity requirements that would today result in transverse reinforcement ratios exceeding the nominally-provided ones by a factor of 8 to 10 or more. As a consequence of the low transverse reinforcement and underestimated flexural over-strength, the I-10 structures at Fairfax & Washington, and at La Cienega and Venice, collapsed with column shear failures either before or shortly after their initial flexural yielding. Quantitative failure assessments of these structures [Priestley, Seible and Uang, 1994] showed that the failure modes encountered could have been prevented with available column retrofit jacketing technology.

Retrofit designs for both of the collapsed I-10 structures were complete at the time of the Northridge earthquake. However, retrofit implementation reportedly was compounded by problems concerning the leased airspace under the La Cienega and Venice structures, reemphasizing the fact that time is of essence in the seismic retrofit program.

### BRIDGES DESIGNED BEFORE 1971 BUT CONSTRUCTED AND/OR COMPLETED AFTER 1971

The second group of bridge structures, the I-5/SR-14 Antelope Valley Interchange, were designed to pre-1971 design standards, but were completed in 1974. This suggests that lessons learned from the 1971 San Fernando earthquake should have been implemented in the redesign.

A common misconception following the Northridge earthquake was that the same bridge structures that collapsed during the 1971 San Fernando earthquake collapsed again this time. Pre- and post-earthquake aerial photographs [Jennings, 1971], clearly show that:

1. The 1971 bridge collapse was in a different separation structure, namely the I-5/SR-14 south separation and overhead.
2. During the 1971 San Fernando event, two bridge sections that collapsed in the Northridge earthquake were under construction (SR-14/I-5 south connector overcrossing spans 1 and 2 had the bottom soffit, webs and cap beams cast), or were almost complete (the SR-14/I-5 North Connector Overcrossing was complete, with the exception of one column and the last two spans at the north end).
3. All columns in the Antelope Valley Interchange, except for the one mentioned above in 2, were completed and featured the nominal pre-1971 #4 @ 12 in. transverse column reinforcement.

Because unseating at expansion joints in tall bridges with single-column bents was identified as the primary reason for collapse of bridge structures in the 1971 San Fernando earthquake, the decision at the time must have been to complete the interchange with the already built substructures, but with added expansion joint restrainers to tie the superstructure together and prevent unseating at expansion joints.

During the Northridge earthquake, the two bridge failures at the I-5/SR-14 Interchange can be attributed to brittle shear failure of short or stiff columns. These columns, proportionally to their stiffnesses, attracted more seismic force than their more flexible adjacent bents and did not have the necessary deformation capacity due to the pre-1971 transverse reinforcement detailing [Moehle et al, 1994, Priestley, Seible and Uang, 1994]. In addition, the shear failure of the north connector of bent #2 was aided by an effective shortening of the column by the construction of a truck ramp shoulder strip around the column with compacted aggregate and asphalt/concrete overlay. Thus, both structures at the I-5/SR-14 Interchange collapsed by brittle shear failure in the short columns next to the abutments with subsequent superstructure unseating at the abutment and superstructure flexural failure at the adjacent bent as a direct consequence of the short column collapse.

### BRIDGES DESIGNED AND BUILT AFTER 1971, BUT BEFORE BASIC DESIGN CONCEPTS WERE CHANGED IN 1987

Finally, the two bridges that failed on the SR-118 Simi Valley-San Fernando Freeway at Mission & Gothic and Bull Creek Canyon were clearly post-1971 vintage in both design and construction. Both bridge failures during the Northridge earthquake can be attributed to:

1. Significantly increased stiffness due to decrease in length or effective column-shortening by heavy column flares at Mission & Gothic, and by a channel wall at Bull Creek Canyon that was built integral with the columns along a bent line.
2. Higher shear demands due to flexural over strength and reduced effective length; and,
3. Degrading shear capacities under inelastic cyclic loading at high ductility demand.

At the Mission & Gothic Undercrossing, the column flares, extending over half the column height, were moderately reinforced along the flare. These moderately reinforced flares more than doubled the flexural capacity of the column top in the flared column direction. Transverse reinforcement, in the form of a smooth #5 spiral with 3.5" pitch, was provided along the entire circular column core, and flexural plastic hinging was forced to the bottom of the flare. The increased shear demand led to shear failure and vertical column bar buckling in the plastic hinge region at high local curvature ductilities. At Bull Creek Canyon, only the column ends over a distance of one column diameter were confined with tightly spaced spirals, while the column center portion featured again a 12" pitch. In the bents with the integral channel wall, the channel wall top was clearly in the region of low transverse reinforcement ratio that provided little or no ductility to the inelastic flexural hinge that formed on top of the channel wall and failed in shear at low flexural ductilities [Priestley, Seible and Uang, 1994].

### SUMMARY

Following the Northridge earthquake there was speculation that blamed the collapse of bridge structures on:

1. Short seat width at expansion joints.
2. High vertical accelerations.

Unseating of the failed bridge sections at the abutments and expansion joints as the primary collapse source would have required significantly larger displacements at the collapsed bents than the available displacement capacities at these bents. Therefore, the bents would have failed before unseating could have occurred. With the exception of Gavin Canyon, the likely failure sequence started with column shear or flexure/shear failures, with unseating as a direct consequence of the shortening or collapse of the adjacent bents.

Vertical ground accelerations measured during the Northridge earthquake were not disproportionately larger than the measured horizontal accelerations, when compared with other earthquakes, [Earthquake Spectra, 1995, pp. 39]. All the described bridge failures can be explained by only the probable horizontal accelerations at the respective bridge sites [Priestley, Seible and Uang, 1994], without contributions by, or interaction with, vertical ground accelerations.

**Design.** The collapsed bridge structures seem to have been designed based on the best available information at the time of the design (pre-1971). Changes during the construction phase of some of these structures (i.e., the I-5/SR-14 bridges) were not feasible, since all columns and most superstructures were already completed at the time of the 1971 San Fernando earthquake and the primary cause of collapse of tall single column structures was attributed to unseating and in-span expansion joints. Retrofit of these bridge structures with expansion joint restrainers was implemented immediately following the San Fernando earthquake.

**Retrofit Delays.** Subsequent upgrading of these first-generation restrainer retrofits and column retrofit implementation was pending adequate funding and a lack of comprehensive seismic design research results until the 1989 Loma Prieta earthquake. The increased funding following Loma Prieta accelerated the retrofit program and retrofit designs were completed for the I-10 structures, but had not yet been implemented at the time of the Northridge earthquake. Problems with leased airspace at La Cienega & Venice, under the bridge structures, have been cited as part of the cause of the delay in retrofit implementation.

The I-5/SR-14 structures were scheduled for retrofit evaluation and design, somewhat lower on the Caltrans prioritization list, due to the post-1971 construction completion date. The retrofit design was also delayed by the classification of the I-5/SR-14 Interchange in an Alquist-Priolo Special Study Zone and appropriate studies on possible faulting and maximum expected vertical and horizontal offsets had been initiated but not yet completed.

**Retrofit Screening Criteria.** The SR-118 bridges were originally on the assessed risk priority list, but were subsequently removed due to various criteria such as no internal expansion joints, post-1971 design and construction, and redundancy in the multi-column bents. The reduced effective length of bridge columns through flares, channels or barrier walls, and ground surface modifications are apparently not routinely checked as part of the Caltrans structural vulnerability assessment.

These structural vulnerabilities of effective column shortening, the effects of heavy uni-directional skew geometry, and a better assessment of flexural over strength and actual shear capacities, are known problem areas and need to be incorporated into the routine vulnerability assessment of bridge structures as quickly as possible.

**Retrofit Would Have Prevented Collapse.** A quantitative assessment of how effective state-of-the-art bridge retrofit technology [Priestley, Seible and Uang, 1994] developed for and by Caltrans over the past eight years shows that all seven of the Northridge earthquake bridge collapses could have been prevented with current seismic retrofit technology. Thus, the critical elements were not a lack of technical understanding or design errors, but rather oversights in the structural vulnerability assessment and, most importantly, the retrofit implementation time factor.

## 5. CALTRANS BRIDGE DESIGN AND RETROFIT PROGRAM

### EVOLUTION OF CALTRANS BRIDGE DESIGN PRACTICES

In 1943, the California State Division of Highways introduced a specific static seismic lateral load requirement into its design specifications for the first time. Bridge design, at that time, considered an equivalent lateral seismic load as a percentage of the dead weight. The percentage varied from 2 to 6 depending upon the soil conditions. Two percent, four percent, and six percent were specified for bridges founded on rock, on soils having 4 tons/ft$^2$ bearing capacity, and on piles, respectively.

In 1963, the Division's Bridge Department adopted the Structural Engineers Association of California (SEAOC) code formulation requiring that the equivalent lateral seismic load (EQ) be determined using the formula EQ = KCD in which D is the dead load of the structure, C is a seismic base-shear coefficient given by $0.05/T^{1/3}$ (T being the fundamental period of the structure) with 0.10 specified as an upper limit, and K is a coefficient representing energy absorption capacity of the structure. A K-value of 1.33 was specified for bridges having wall supports with height-to-length ratios of 2.5 or less, 1.00 was specified for bridges having single-column or pier supports with height-to-length ratios greater than 2.5, and 0.67 was specified for bridges supported on continuous frames. The design provision also specified that the product KC should never be less than 0.02.

In hindsight, and as was demonstrated by the San Fernando earthquake, using building design provisions for bridges was not appropriate. Bridges and buildings share some characteristics, but differ in fundamental ways that make their behavior very different. The building provisions expressed the profession's evaluation of the totality of a building's characteristics and their expectation of its performance in an earthquake. The provisions should only have been used for structures that are similar to buildings, which bridges are not.

The damages to bridge structures during the San Fernando earthquake made it very clear that the above 1963 code provision was inadequate. Thus, the California State Division of Highways immediately instituted changes to increase the 1963 code force level by the factor of 2 for all bridges supported on spread footings and by the factor 2.5 for those bridges supported on pile foundations. Besides increasing the code force level, many structural details were improved considerably. These changes applied only to new designs. Caltrans knew that many of the deficient bridge structures in use were designed using the pre-1971 design criteria, and, consequently, initiated a seismic retrofit program.

A brief chronological summary of some of the major developments in these criteria is given below:

**1971-1986.** Research results from the 1971 San Fernando earthquake, as well as recommendations developed by the ATC-6 project caused Caltrans to implement new bridge design criteria. During this period, ARS (acceleration response spectrum) ground motion curves and response reduction factors were adopted, which, in general, led to higher design force levels and the specification of robust spiral ties for columns was implemented.

**1986-1989:** A retrofit program developed by Caltrans identified single-column bridge bents as being potentially the most vulnerable to earthquake damage. Research sponsored by Caltrans at the University of California, San Diego, led to a retrofit procedure that uses steel jackets to increase flexural ductility and shear capacities. Immediate implementation was begun for these bent types.

**Post-1989:** Following the 1989 Loma Prieta earthquake, Caltrans sponsored accelerated retrofit research primarily conducted at the University of California at Berkeley (UCB) and University of California at San Diego (UCSD) and appointed a Seismic Advisory Board. Peer review panels were selected for the retrofit or replacement of the damaged San Francisco viaducts. The Applied Technology Council project (ATC-32) was initiated to review and revise bridge design criteria. While the draft results of this project are available and have been partially adopted by Caltrans, the project has yet to be completed. Administrative issues have held up the contract for the final period.

Although Caltrans design criteria have not been formally revised, ad hoc criteria and design memoranda have been developed and implemented for replacement, as well as retrofit, of existing bridges. These revised or supplementary criteria include guidelines for development of site-specific ground motion estimates, capacity design to preclude brittle failure modes, rational procedures for joint shear design, and the definition of limit states for various performance objectives.

Hinge restrainers had been installed in a total of about 1,200 bridges in Los Angeles County since the 1971 San Fernando earthquake. At the time of the Northridge earthquake, Caltrans had identified 716 high-risk bridges for retrofit in Los Angeles County—retrofit had been completed for 115 of these bridges, consisting chiefly of steel jackets and footing strengthening at single-column bents.

In 1990, a total of 700 city and county bridges were targeted for retrofit. Only a small number of these were complete at the time of the earthquake, due to funding limitations.

### BOARD OF INQUIRY INVESTIGATION

A post-Loma Prieta earthquake review was conducted by a Board of Inquiry appointed by Governor George Deukmejian on October 26, 1989. After extensive hearings and studies, the Board submitted its findings and recommendations to the Governor in a comprehensive report, *Competing Against Time*, May 31, 1990, [Housner, 1990a, 1990b]. This report gave specific recommendations for action by the Governor, the Director of the Department of Transportation, and transportation agencies and districts. On June 2, 1990, Governor Deukmejian issued Executive Order D-86-90, [Governor, 1990], to implement the Board of Inquiry's recommendations, which contained the following items of importance to Caltrans programs.

1. It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings.
2. The Director of the Department of Transportation shall prepare a detailed action plan to ensure that all transportation structures maintained by the State are safe from collapse in the event of an earthquake and that vital transportation links are designed to maintain their function following an earthquake. The plan should include a priority listing of transportation structures which will be scheduled for seismic retrofit. The Director shall transmit this action plan to the Governor by August 31, 1990.
3. The Director of the Department of Transportation shall establish a formal process whereby the Department seeks and obtains the advise of external experts in establishing seismic safety policies, standards, and technical practices; and for seismic safety reviews of plans for construction or retrofit of complex structures. The Director shall transmit a summary of this process to the Governor by August 31, 1990.
4. The Director of the Department of Transportation shall assign a high priority to development of a program of basic and problem-focused research on earthquake

engineering issues, to include comprehensive earthquake vulnerability evaluations of important transportation structures and a program for placing seismic activity monitoring instruments on transportation structures. The Director shall transmit a description of the research program to the Governor by August 31, 1990.

### CALTRANS RESPONSE TO BOARD OF INQUIRY RECOMMENDATIONS

Caltrans made fundamental changes in its operations in response to the Board of Inquiry recommendations, and has taken actions to fulfill these requirements on a priority basis, [Thiel, Housner, and Tobin, 1991]. In particular the Division of Structures under James Roberts has responded positively and quickly to these recommendations, issuing annual status reports [Caltrans, 1994]. In response to the recommendations Caltrans:

1. Appointed a Seismic Advisory Board to review its programs and advise on technical and administrative programs, bringing oversight and contributions from an extended community of earthquake engineering specialists. It has met approximately quarterly since then to review and advise Caltrans on proposals, progress, and implementation actions to meeting the recommendations.
2. Developed an action plan to assure seismic safety of state-owned bridges.
3. Performed vulnerability assessments of the 24,000 state, county, and city bridges and a developed prioritized list to implement a seismic retrofit program.
4. Developed a bridge seismic performance policy.
5. Implemented independent technical peer review of the seismic aspects of important projects, thus opening their design process to influence by a broader technical community.
6. Developed a priority list for the retrofitting of high hazard structures based on a rational procedure.
7. Initiated seismic retrofit design and construction for approximately 2,000 high-hazard structures to be completed over a 10 year period (1989-1999).
8. Instituted changes to the Caltrans Bridge Seismic Design Specifications and Criteria.
9. Established an Office of Earthquake Engineering and conducted extensive training in seismic design for over 200 bridge engineers.
10. Increased commitment to research funding with an initial investment of $8 million, followed by annual expenditures of $5 million on problem-focused seismic research topics.

The above actions are in various stages of progress and will require a continuing management commitment to their completion. The Seismic Advisory Board evaluated Caltrans performance as consistent with the directions of the Executive Order and legislative directions on seismic safety.

### PEER REVIEW

In response to the Board of Inquiry report, Caltrans implemented a seismic safety peer review process for selected important new or retrofit bridge design projects following the Loma Prieta earthquake. The peer reviews to date have had several different forms and functions. The Seismic Advisory Board recommended that the peer review process be standardized to make it even more effective. The scope of review process should be standardized in terms of:

1. Which bridges are to be scrutinized.
2. Scheduling the review to allow designers and reviewers the time necessary to scrutinize and/or improve on the seismic performance of the bridge structure.

3. Completeness of the peer review, starting with the initial concept and strategy of design and type of selection and continuing through the final seismic design detailing.

The specific terms of content or format should not be standardized; they must be project-specific.

Peer review is currently implemented only for a few special structures. Northridge shows that the seismic performance of common structures affects the functionality of the transportation system as a whole. The Board believes that peer review also should be implemented for *some* selected common bridges. This will help ensure that all new and retrofit designs benefit from the best technical knowledge and experience, not just the "important" structures. What makes a bridge "important" needs review and clarification in light of the regional transportation system so that it will be clearer to the public and better defined for engineering design purposes.

As a very positive note, it should be stated that experiences with the peer review process to date indicate that peer review seems to be the vehicle that integrates the latest seismological, geological, geotechnical and structural findings into Caltrans seismic design for bridges and bridge retrofits.

### PEER REVIEW AND CONSTRUCTION OF THE NORTHRIDGE EARTHQUAKE REPLACEMENT BRIDGES

Caltrans set a very fast schedule for the removal of all collapsed and unsafe bridges, the replacement of nine bridge structures, and the retrofit of one bridge—all to be completed by December 1, 1994. This schedule provided new challenges not only for demolition and construction, but also for design and seismic safety review. Demolition and construction contracts were given on an invited, prequalified limited bid basis with heavy incentive and penalty clauses for early or late completion, respectively. For this reconstruction effort design submittals were staged to just stay ahead of the construction, and the seismic safety review is based on evolving and continuously changing design concepts and documents.

Nevertheless, Caltrans is implementing significant changes from past design practice based on lessons learned from the Northridge earthquake in terms of:

1. Elimination of most in-span expansion joints through longer jointless superstructures or special hinge bents.
2. Elimination of excessively skewed joints and abutments.
3. Balancing the stiffness of bridge columns within individual frames.
4. Design alternatives in steel and concrete for selected structures.
5. Use of site-specific geological and seismological data for ARS curves and substructure stiffness.
6. Consideration of potential vertical excitations for the superstructure.

All these new concepts, and the associated changes and deviations from established design procedures, were implemented and accomplished in this short period. This indicate a commendable flexibility and capability of Caltrans designers and engineering consultants. The Board believes that the public can have confidence in the seismic safety of these replacement structures.

### CALTRANS RETROFIT AND DESIGN RESPONSE TO LOMA PRIETA EARTHQUAKE

As required by the Governor's Executive Order D-86-90, Caltrans appointed Peer Review Panels consisting of private practitioners, academicians and researchers to evaluate the work of the Caltrans and its consultants. The peer review panels held regular meetings to review both retrofit criteria and methods, resulting in substantial changes in the work underway. In the case of the San Francisco Double Deck Freeway retrofit program, a number of major issues surfaced. Poor soil conditions led to the need for site specific analyses because existing ARS curves were not felt to be appropriate. Major deficiencies of the original structures were in the areas of insufficient joint shear reinforcing; inadequate reinforcing steel anchorage and laps; large torsion resulting from freeway configuration; and the absence of longitudinal frame action. Rather than an incremental retrofit program, where the first step would permit the opening of the freeways to traffic and the second step would refine the retrofit to provide for post earthquake operational capacity after a future major earthquake, it was decided to combine this work into a single effort.

### PRIORITIZATION AND SCREENING PRACTICES

Caltrans experience with retrofit of the damaged bridges in the San Francisco Bay area following the Loma Prieta earthquake in 1989 emphasized the need for a "structural systems" approach to the retrofit of older, seismically deficient bridges instead of a "structural elements" approach. With the support of the Seismic Advisory Board, Caltrans initiated a comprehensive retrofit program.

The decision on whether a bridge should be considered for retrofitting is based on a five - step process for prioritizing structures for retrofit. At any step in the process, a structure can be assessed as acceptable and not further considered.

Screening procedures for retrofitting structures are developed in five steps:

1. A computerized prioritization algorithm was developed to evaluate the various attributes of each bridge and to assign a quantified ranking for retrofit . It employs three major categories for evaluation: 1) vulnerability of structures; 2) seismic hazard; and 3) impact on the community. Each of these categories has a number of specific elements (Table 5-1).
2. Initial screening of the approximately 24,000 state, county, and city bridges in California to determine their seismic vulnerability . About 7,000 state bridges and 4,000 county and city bridges were identified as being potentially hazardous.
3. Detailed plan review of all 11,000 potentially hazardous bridges.
4. Detailed seismic evaluation of the remaining bridges in order of priority to identify structural deficiencies for retrofit (see Table 5-2).
5. Design and preparation of the necessary construction documents to implement the retrofit. Unlike prior retrofit programs, this program systematically addresses deficiencies in all the structural components of each bridge.

Initially there were 11,895 state highway bridge structures to be ranked. Of this group, 2,537 were judged to be hazardous, although since not all third-step studies are complete, this number may be reduced. Table 5-2 shows the sequence of reductions in numbers at the three assessment steps of the review, yielding a best estimate at this time of about 2,000 bridges that will need retrofitting. Of these 2,000 high-risk bridges, 716 were in Los Angeles County. Engineering design has been completed for 800 bridges in the State; construction has been completed for 250; approximately 400 are in the process of being retrofitted.

Although most state bridges were screened out of the current retrofit program, this does not mean that they satisfy modern design and construction standards. At a later date, further consideration must be given to the potential for severe damage or collapse.

*Table 5-1. Weights used in the prioritization process. ; The priority is determined from the formula below where $A_f$ is the fault activity (0.25-1.0), $H_f$ is the sum of the hazard characteristic values, $V_f$ is for vulnerability and If for Impact. Specific characteristic values range from zero to the maximum value given based on the characteristics of an individual bridge.*
*Priority rating index = $(A_f H_f)(0.60 I_f+0.40 V_f)$*

| Category/characteristic | Characteristic Weight |
|---|---|
| Hazard ($H_f$) | |
| Soil conditions | 33% |
| Peak rock acceleration | 38% |
| Duration | 29% |
| Vulnerability ($V_f$) | |
| Year designed | 25% |
| Outriggers or shared columns | 22% |
| Abutment type | 8% |
| Skewness | 12% |
| Drop type failure | 16.5% |
| Bent redundancy | 16.5% |
| Impact ($I_f$) | |
| ADT on structure | 28% |
| Leased air space (residential, office) | 15% |
| Leased air space (parking, storage facility) | 7% |
| ADT under/over structure | 12% |
| Facility crossed | 7% |
| Route type on bridge | 7% |
| Detour length | 14% |
| Critical utility | 10% |

## 1994 STATUS OF STATE HIGHWAY BRIDGE RETROFIT PROGRAM

A total of 2,537 state bridges remain in the current retrofit program based on the screening procedure discussed above. Further screening and preliminary structural evaluation have resulted in identification of about 2,000 state bridges that require detailing evaluation and retrofit. As indicated in Figure 5-2, retrofit plans have been completed for approximately 800 bridges, bids have been opened for 400, and retrofit has been completed on about 250.

The retrofit program for state highway bridges has been divided into three parts—single-column, multiple-column, and toll-bridge programs—with a total estimated cost of $2,420 million (Table 5-3). All projects are in progress with the indicated percentages for structures with construction complete, and under construction. Figure 5-1 graphically illustrates the proportion of structures impacted in each of the nine project categories from *Ready For Assignment* to *Construction Completed.*

*Table 5-2. Status of the retrofit review of State highway bridges.*

| Stage | Number |
|---|---|
| Total bridges on the state highway system | 11,895 |
| Total screened out in first screening (priority index) stage | 4,612 |
| Total screened out in second screening stage (plan review) | 3,595 |
| Total screened out in third screening stage (detailed dynamic analysis) | 1,151 |
| Total remaining in the retrofit program; some will be dropped as the detailed analysis continues | 2,537 |

*Table 5-3. The Caltrans bridge retrofit program status as of June 1, 1994. The proportions are based on the total number of structures affected. M is an abbreviation for millions. (Caltrans 1994)*

| | Category of structure | Estimated total cost | Construction complete | Construction underway | Remaining |
|---|---|---|---|---|---|
| 1. | Single column retrofit | $120 M | 87% | 13% | 0% |
| 2. | Multiple column retrofit | $1,650 M | 2% | 7% | 91% |
| 3. | Toll bridge retrofits | $650 M | 0% | 0% | 100% |

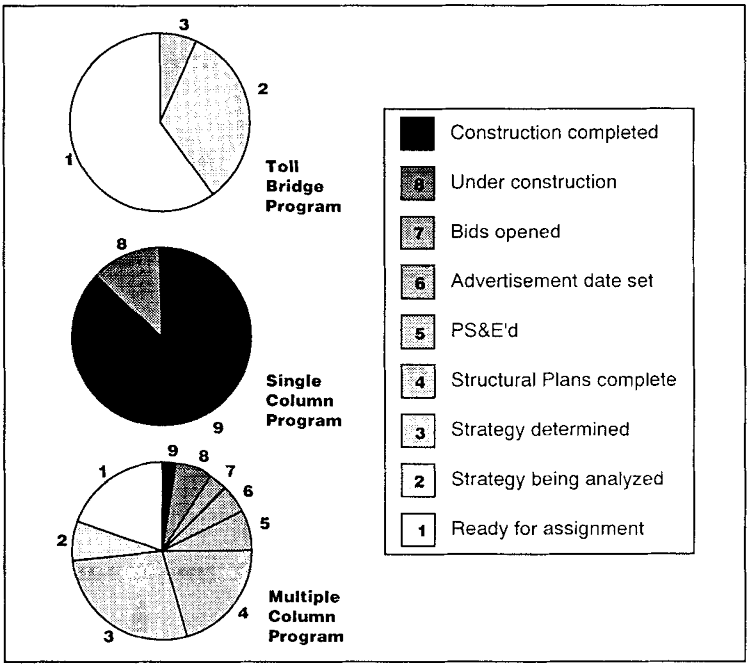


*Figure 5-1. The pie charts show the status of the single-column, multiple-column and bridge retrofit programs for state highway bridges. The segment represents the proportion of the structures in the particular category of completion compared to the number of structures affected.*

Figure 5-2 graphically emphasizes the remaining vulnerability of the state highway system. In particular, it should be noted that retrofit plans have not yet been completed for any of the 11 toll bridges in California. Most of these bridges, such as the San Francisco Bay Bridge, are vital to the economic welfare of the area they serve.

None of the toll bridge retrofit projects were yet in construction by April, 1995. These bridges are complex structures, requiring substantially more design effort than do conventional bridges. The seismic retrofit program for these structures has been approached in three parts:

1. Hazard analysis
2. Vulnerability analysis
3. Design planning, specifications and engineering (PS&E)

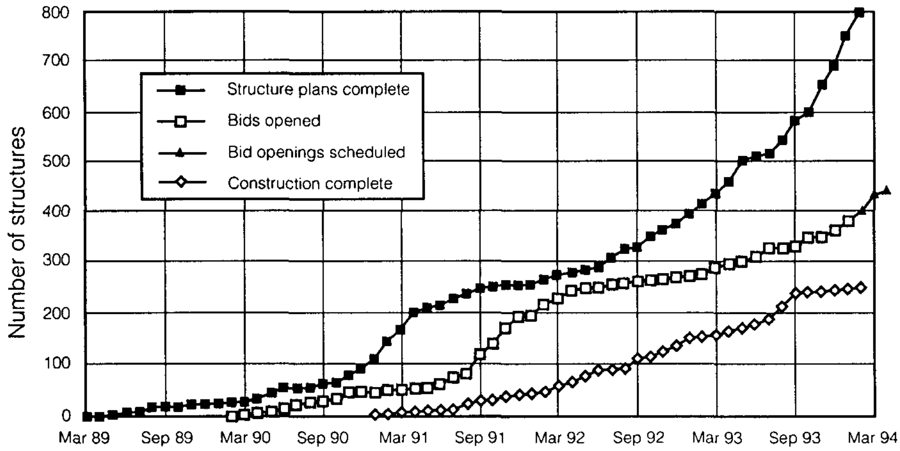


*Figure 5-2. The total numbers of seismic safety retrofit projects for state highway bridges in different stages of completion since March 1989. Note that the program accelerated substantially following the Loma Prieta earthquake on October 7, 1989.*

Table 5-4 gives the status of these studies for each of the 11 toll bridges for which Caltrans is responsible. Hazard analyses have been completed for all the toll bridges, with the results having been made available for vulnerability assessments. Vulnerability analyses are complete for some of these bridges and retrofit designs are underway.

## SUMMARY

In summary, the 1971 San Fernando and the 1989 Loma Prieta earthquakes both had a major impact on increasing the awareness of the seismic risks to bridge structures in California. Following the Loma Prieta earthquake, Caltrans responded positively to the recommendations of the Governor's Board of Inquiry for improving the seismic safety of highway bridges outlined in *Competing Against Time.*

*All* post-Loma Prieta retrofitted bridges performed well in the Northridge earthquake. All of the bridges in the region of strong motion are in the "common" class. Of the seven bridges that collapsed, five had been identified and scheduled for seismic retrofit. Two, the Mission & Gothic Undercrossing and Bull Creek Canyon Channel Undercrossing on State Route 118, had been evaluated as not currently requiring retrofit . In light of this experience, it is advisable to review the prioritizing procedure and reexamine the retrofit decision for those bridges that were eliminated from the retrofit program to determine if they should be reconsidered. The seismic safety of common other bridges should also be examined for possible retrofit.

It is essential that retrofit of the remaining deficient bridge structures in California be accelerated so that, hopefully, it will be completed before the next major earthquake occurs. Whatever actions and support are required to accomplish this must be provided by the Governor and the State Legislature.

*Table 5-4. Status of Toll Bridge seismic studies in April, 1994. The dates given are those when the phase of the study was completed or is scheduled to be completed; T indicates target, C indicates completed, and * indicates that the target dates is based on Caltrans' ability to contract work with consulting engineering firms.*

| Bridge | Date of completion or scheduled completion Hazard | Vulnerability | Design PS&E |
|---|---|---|---|
| San Francisco-Oakland Bay Bridge (12 distinct design projects)[1] | | | |
| West spans | C 12/92 | T 8/94 | T 6/96 |
| East spans | T 5/94 | T 5/94 | T 6/96 |
| Dumbarton Bridge | C7/93 | T 5/94 | Unscheduled* |
| San Mateo-Hayward Bridge | C 2/93 | C 11/93 | T 6/96* |
| Richmond-San Rafael Bridge | C 6/93 | T 12/94 | T 6/96* |
| Carquinez Bridge | C 2/93 | C 12/93 | T 6/96* |
| Benicia-Martinez Bridge | C 12/92 | C 8/93 | T 6/96* |
| Antioch Bridge[2] | C 9/93 | T 5/94 | Unscheduled* |
| San Diego-Coronado Bridge | T 7/94 | C 7/95 | T 6/96* |
| Terminal Island (Vincent Thomas) Bridge | T 7/94 | C 11/91 | T 6/96* |
| Commodore Schuyler Heim Bridge[3] | T 12/94 | N/A | N/A |
| Terminal Island (Gerald Desmond) Bridge[5] | T 12/94 | N/A | N/A |

Notes 1. Some retrofit construction is complete (Pier E-9), having been initiated immediately after the Loma Prieta earthquake; other construction will be initiated in the summer of 1994 and continue until all projects are completed.
2. A recently completed design that may require retrofit work.
3. This bridge is on soft ground over an oil field that has been settling for years. No amount of retrofitting would guarantee continued operation.
4 Bridge built by the Port of Long Beach. It will become part of the state highway system in the near future. Caltrans is negotiating an agreement to have Port bring it up to current maintenance standards before acceptance. Seismic vulnerability studies will be initiated upon acceptance.

## 6. IMPROVING THE CALTRANS SEISMIC PROGRAM

### RETROFIT PRIORITIZATION PROCEDURES

The Northridge earthquake has shown that the ambitious retrofit prioritization program undertaken by Caltrans for all of the State's 24,000 bridges has been effective. However, it is not flawless and needs continued scrutiny and updating. This section presents some of the Seismic Advisory Board's suggestions for improvement based on observations of system performance in the Northridge earthquake and reconsideration of some past decisions Caltrans has made.

It can be argued that the uncertainties in assessing seismic hazard and the complexities of determining structural vulnerability cannot be quantified into a deterministic, numerical risk assessment and retrofit prioritization. Caltrans is well aware of this argument. The Caltrans risk assessment algorithm, which has been continuously modified and updated over the past three years, is only used as a *prescreening* tool. All the bridge structures that collapsed in the Northridge earthquake were initially identified as potential retrofit candidates using this algorithm. However, two of these were removed from the list on the third step of screening.

The subsequent manual screening of all identified candidate structures relies heavily on subjective judgments by individual review engineers and, consequently, is prone to error and omissions. Caltrans tries to minimize these problems by having at least two independent reviews, with arbitration in case of differences. The fact that only two bridges of 506 bridges located within the strong shaking area (PGA≥0.5g) were misjudged by the Caltrans risk assessment procedure is actually quite remarkable.

After a preliminary assessment of observations from the Northridge earthquake, the Seismic Advisory Board suggests the following actions be taken by Caltrans:

1. Review of Phase I expansion joint retrofits in terms of restrainer orientation, restrainer capacity, detailing and seat width extension, and vulnerability of columns.
2. Train review engineers to look for effective length of columns as modified by flares, walls, or ground surface conditions.
3. Train review engineers to assess potential ductile vs. brittle failure modes in columns.
4. Rescreen all bridge structures based on the latest hazard and vulnerability findings.

These actions should be incorporated as expediently as possible into the retrofit prioritization procedure and training programs.

While almost all bridge design is based on linear elastic methods, damage is caused by nonlinear response. Linear elastic design methods are formulated so that they provide adequate nonlinear response in most cases. While linear approaches may be quite serviceable in most cases, some applications require non linear analysis to properly understand the structures' response and judge the adequacy of a design. Nonlinear analysis can be applied both to dynamic time history and static approaches, in the latter case push-over analyses are one commonly used approach. The Board believes it to be important that Caltrans develop the staff capable of performing nonlinear analyses for both complete bridge systems and for sections of bridges. It further believes that all Caltrans design engineers should be well informed as to the limitations of linear elastic analysis and the circumstances when each is appropriate.

Finally, retrofit designs, and particularly implementations, need to proceed as quickly as possible for all bridge types, without consideration of restrainers first, single-column bents second, multi-column bents third, and toll bridges separately or fourth. The highest risk (including the greatest consequence of failure) is likely to be found to be independent of the these basic types of categories.

The Board believes that the methods used to assign priority needs rethinking. The current system uses one index to determine the priority and it may not be robust enough to order bridges properly. It may be necessary to use more complicated approaches than the current one. Future priority assignment systems must recognize all of the factor and specific characteristics for each bridge that contribute to its hazard, vulnerability, and importance valuations.

### SITE-SPECIFIC STUDIES

The Northridge earthquake indicates the importance of undertaking specific geotechnical studies for all new designs or retrofits of major bridges and for sites that are expected to perform poorly. The evidence of the Northridge earthquake is that motions at several of the collapsed bridges may have been significantly amplified by the local soil conditions. Current weighting factors in the prioritization procedure apply too little weight to the geotechnical conditions of the site and their variations along the length of a structure.

### USE OF EARTHQUAKE PREDICTION FOR PRIORITY SETTING

The Northridge earthquake could not have been forecast as to specific place, time and size. Though it occurred on a blind-thrust fault, it was not unexpected, because it lies within in a broad region where such active faults are known to occur.

In general, quantitative statements on the probability of future earthquakes are of limited value in deciding Caltrans retrofit priorities. Nevertheless, when the importance factors for structures are considered, there are certain tectonic regions of the State where the likelihood of intense strong motions in the lifetime of the structures can be specified with some confidence. This geological and geotechnical knowledge, where available, should guide the design of new structures and the prioritization for retrofit of structures.

### RESEARCH SHOULD BE ENHANCED

Caltrans has made a commitment to support research and development, and has sustained a $5 million per year research program on bridges since the Loma Prieta earthquake. The evidence suggests that it will continue this commitment. There is, however, more to do than this budget commitment allows. It is essential that the Caltrans comprehensive seismic bridge retrofit research program be continued and accelerated to address the behavior of bridges as complete, interconnected systems, including soil effects. Research should focus not just on safety or "no collapse" criteria, but also on functionality or serviceability criteria that clearly outline the expected bridge damage, reparability, and bridge or route closure consequences.

The focus of research and professional practice development to date has been on reinforced concrete and older steel bridges. Observed damage to modern steel buildings suggests that there may be serious seismic performance problems associated with current design and construction procedures for steel bridges. These issues need to be investigated with the objective of ensuring that Caltrans bridge designs are not subject to the same types of failure problems.

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