2614

LONG SPAN BRIDGES IN CALIFORNIA - SEISMIC DESIGN AND RETROFIT ISSUES

Frieder SEIBLE[1]

SUMMARY

California's toll bridges are unique, long span and complex structures and their continued functionality is of significant importance to the social and economical vitality of the State. The California Department of Transportation (Caltrans) is directly responsible for nine of California's ten toll bridges (since the Golden Gate Bridge is administered through an independent bridge district). In addition to the Golden Gate, these toll bridges are at Antioch, Benicia-Martinez, Carquinez Strait, Richmond-San Rafael, San Francisco-Oakland Bay, San Mateo-Hayward, and Dumbarton in Northern California and Vincent Thomas and San Diego-Coronado in Southern California. The retrofit design for the San Francisco-Oakland Bay Bridge was performed by Caltrans in-house. Antioch and Dumbarton are relatively new and were judged by Caltrans not to require seismic retrofit at this time. The seismic assessment and retrofit for the other six toll bridges was performed for Caltrans by outside consulting engineering firms. In addition to retrofitting the existing long span toll bridges, Caltrans has also embarked on the consultant design and construction of three new long span bridges, either as additional parallel structures to existing bridges such as Benicia-Martinez or as replacement bridges in the case of the San Francisco-Oakland Bay Bridge (SFOBB) East Bay and the Carquinez Strait. Seismic design and retrofit considerations and procedures for these new and existing California toll bridges are discussed.

INTRODUCTION

California's transportation infrastructure and its local and regional economy rely heavily on the 10 existing and 3 new long span toll bridges which connect major urban areas and are an integral part of the interstate freeway network. Recent earthquakes such as Loma Prieta (1989) [Housner, et al, 1990] and Northridge (1994) [Housner, et al, 1994] have shown the vulnerability of bridges to seismic motions and the consequences of partial or complete bridge failures to the transportation of people, goods, and services. Due to the importance of the long span toll bridges as transportation lifelines following a large seismic event for emergency response and subsequently for the regional recovery, special assessment, design, and retrofit efforts are made to achieve reliable seismic performance of these bridges under all probable earthquake ground motions for the particular bridge site.

The California Department of Transportation (Caltrans) is directly responsible for nine of the ten existing toll bridges, namely (1) Antioch, (2) Benicia-Martinez, (3) Carquinez, (4) Richmond-San Rafael, (5) San Francisco-Oakland Bay (6) San Mateo-Hayward, (7) Dumbarton, (8) Vincent Thomas, and (9) Coronado. The tenth toll bridge, namely the Golden Gate Bridge, is administered, operated, and maintained through a separate bridge authority. The general locations of these ten toll bridges are depicted in Fig. 1. All ten existing long span toll bridges are currently retrofitted for reliable seismic performance. In addition to these ten existing toll bridges, three new long span bridge structures are currently in the planning and design process to ensure a reliable freeway transportation network for the 21st Century. While the span lengths of these toll bridges no longer set any records in the world-wide bridge inventory, the design challenges for both, retrofit and new construction rests with the high seismicity in California and the performance/functionality requirements following various earthquake design events.

Compared to most other long span bridges world-wide, California's toll bridges carry very high traffic volumes, see Table 1, and retrofit construction has to be performed under full traffic with only limited allowances for lane

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[1] *Dept of Structural Engineering, University of California, San Diego, La Jolla, CA 92093-0085, seible@ucsd.edu*

closures in off-peak hours. The total estimated costs for the toll bridge retrofit is $1,126,000 and the estimated cost for the construction of the three new toll bridges is $1,872,000. A detailed summary of individual toll bridge data on year of construction, average daily traffic, bridge length, main span type and main span length is provided in Table 1, together with estimated retrofit/new construction costs.

Figure 1. Location of California's Toll Bridges

PERFORMANCE CRITERIA

The seismic performance expectations for California's toll bridges vary for the different bridge structures. While all bridge retrofits have to be designed to meet the "no-collapse" criterion under the Safety Evaluation Earthquake (SEE), the expected performance following the SEE depends on the bridge designation and its importance in the State's transportation highway system. For example, the Benicia-Martinez Bridge is on a designated State Lifeline Route which requires immediate service level following the SEE, whereas significant damage with prolonged closure can be accepted at other bridge locations. In addition to the response under the SEE, the toll bridge retrofit designs also had to address a more frequent moderate seismic design event, namely the Functional Evaluation Earthquake (FEE) to ensure prescribed levels of service, depending on the bridge designation. (Note: For some of the toll bridges, e.g., Richmond-San Rafael, the FEE was relaxed or dropped by Caltrans as a design event). Finally, two of the ten toll bridges, namely Vincent Thomas and Coronado, are crossing potentially active faults with the possibility of ground surface fault offsets within the bridge domain which required a third design level, namely the Fault Rupture (FR), to be considered in conjunction with the "no-collapse" performance requirement. A summary of the Caltrans multi-level design approach with descriptive performance levels for different bridge designations is provided in Table 2, together with general definitions of the SEE, FEE and FR design events.

Table 1. California's Toll Bridges

	Bridge	Const. Completion (Year)	Avg Daily Traffic (# of Vehicles)	Total Length (m)	Main Span Type	Main Span Length (m)	Estimated Retrofit/New Const. Cost ($million)
EXISTING (Retrofit)	Golden Gate	1937	120,000	2,790	Steel Stiffening Truss	1,280	200
	Antioch	1978	30,000	2,880	Twin Corten Steel Girder Composite	140	—
	Benicia-Martinez	1962	100,000	1,896	Steel Truss	161	100
	Carquinez (1927 WB)	1927/1958	111,000	1,022	Steel Cantilever Truss	336	62
	Richmond-San Rafael	1956	35,000	6,309	Steel Cantilever Truss	326	348
	San Francisco-Oakland West Bay Spans	1936	280,000	6,100	Steel Stiffening Truss	705	214
	San Mateo-Hayward	1967	75,000	11,273	Steel Box Girder with Orthotropic	229	112
	Dumbarton	1981	45,000	2,600	Steel Box Girder Lightweight	104	—
	Vincent Thomas	1964	90,000	1,849	Steel Stiffening Truss	450	26
	Coronado	1969	63,000	3,440	Steel Box Girder with Orthotropic	201	64
NEW	Third Carquinez Straits	2003*	111,000	1,028	Orthotropic Steel Box Suspension	728	188
	Second Benicia-Martinez	2003*	100,000	1,653	Segmental RC Lightweight Concrete	161	184
	New San Francisco-Oakland East Bay	2003*	280,000	3,100	Self-Anchored Orthotropic Steel Box	565 total	1,500

*Expected date of completion

Only bridges on designated lifeline routes, such as Benicia-Martinez, as well as all three new long span bridge structures were designed to "Full Performance Level" criteria while for all other toll bridges the "Limited Performance Level" criteria were applied and even those were in some cases relaxed towards the "Minimum Performance Level" where the cost/benefit ratio of the retrofit design did not justify the higher performance levels.

Table 2. Caltrans Seismic Performance Criteria

Ground Motion	Minimum Performance Level	Limited Performance Level	Full Performance Level
Functional Evaluation Earthquake (FEE)	▪ **Immediate Full Service (I)** ▪ Repairable damage within 90 days ▪ Allow lane closures outside peak hours ▪ Minor concrete spalling, joint damage and limited secondary steel members buckling	▪ **Immediate Full Service (II)** ▪ Repairable damage within 30 days ▪ Repairs will require minimum interference with the flow of traffic ▪ Minor concrete spalling, joint damage and limited secondary steel members buckling	▪ **Immediate Full Service (III)** ▪ Minimal damage ▪ Essentially elastic ▪ Minor concrete cracking ▪ minor buckling in secondary steel members
Safety Evaluation Earthquake (SEE)	▪ **No Collapse (I)** ▪ Significant damage with a high probability of repair ▪ Maintain vertical load carrying capacity and a minimum lateral system capacity ▪ Damage may require full closure for public traffic ▪ Repairs will require complete evaluation	▪ **Limited Service** ▪ Intermediate repairable damage ▪ Light emergency vehicles within hours ▪ Reduced public traffic lanes within days ▪ Lateral system capacity is relatively reduced ▪ Repairs within a year	▪ **Immediate Full Service (I)** ▪ Minor repairable damage ▪ Lateral system capacity slightly effected ▪ Minor concrete spalling, joint damage and limited secondary steel members buckling ▪ Lane closure outside peak hours only ▪ Repairs within 90 days
Fault Rupture	▪ **No Collapse (II)** ▪ Extensive damage with low probability of repair ▪ Maintain residual capacity for probable vertical and lateral service loads only	Not Applicable	Not Applicable

Definitions:
FEE: Functional Evaluation Earthquake: The Functional Evaluation Earthquake (FEE) shall be based on the spectra for a 285-300 year return equal hazard (probabilistic) event. This (FEE) corresponds to 60% probability the ground motion not being exceeded during the useful life of these Toll Bridges, considered to be around 150 years.
SEE: Safety Evaluation Earthquake: The Safety Evaluation Earthquake (SEE) shall be based on the Target Response Spectra. For the San Francisco Bay area, the 85th percentile rock spectra for the maximum credible event corresponds approximately to the 1000-2000 year return period equal hazard spectra and was selected as a Target Spectra. For the San Diego and Long Beach areas, motions a little below the 84th percentile deterministic rock motion spectra were selected for Target Spectra. This corresponds approximately to 950-2000 year return period equal hazard spectra.
FR: Fault Rupture: For Fault Rupture (FR) assessment, consult your geotechnical engineer. The findings are subject to approval by a Caltrans consensus group.

For all long span bridge structures in California, the general seismic performance criteria listed in Table 2 are used as a first guideline followed by the development of project specific performance criteria and design guidelines on how these performance criteria can be quantified and met.

SEISMIC DESIGN AND ANALYSIS

The Caltrans toll bridge seismic design/retrofit program which started in 1995 with expected completion in 2003 recognized the importance of the toll bridges in terms of life-safety, functionality, and socio-economic impact for the State of California and expanded the state-of-the-art in seismic response assessment and design in several key areas:

Hazard Definition: Site specific hazard assessments were performed for each of the toll bridges based on controlling source mechanisms, source-to-site parameters and, where applicable, near-source motion characteristics. A consistent methodology and approach were developed by an ad hoc committee of the Caltrans Seismic Advisory Board (SAB) [Seismic Advisory Board, 1998] defining parameters and procedures for the generation of representative rock motion spectra and time-histories, site specific motion development along the entire bridge length, and soil-foundation-structure-interaction models for different soil conditions. In particular, the systematic introduction of near-source effects through adjusted long period fault normal and fault parallel target spectra, as well as consideration of dynamic and kinematic SFSI effects at each pier location were performed for the first time in a consistent approach for seismic bridge design or retrofit.

Nonlinear Analytical Modeling: The significant inelastic response of the retrofitted bridges under the Safety Evaluation Earthquake (SEE) required nonlinear analytical models which can capture all inelastic actions in nonlinear elements, movement joints, hinges and seismic response modification devices to properly capture the most likely response of the bridge. Thus, for the first time, not R or Z-factors (elastic force reduction factors) were employed as the design basis but rather the most probable deformations and forces in the bridge under the SEE design event as a result of multiple sets of nonlinear time-history analyses (THA). This is a significant advancement in the state-of-the-art in seismic response assessment/design and structural differences in the individual bridges required that each design team independently had to deal with these nonlinear analysis/design issues.

Retrofit Design: In order to meet the required performance specifications, in many cases conventional retrofit approaches of strengthening and displacement control did not suffice. Thus, new strategies and concepts needed to be developed which in some cases far exceeded current engineering practice. For example, full isolation of the Benicia-Martinez superstructure resulted in a fully operational bridge after the SEE but required superstructure displacements of ± 4 ft at structural response periods between 3.5 to 5 seconds, a range in which reliable input information becomes sparse and questionable. Many of the toll bridge retrofits resorted to seismic response modification devices (SRMDs) such as isolation bearings and dampers for displacement control and energy dissipation in conjunction with conventional strengthening techniques for capacity protected components. Summary descriptions of the retrofit measures and their assessment are presented in [Seismic Safety Peer Review Panel, 1999].

New Design: The designs of the three new toll bridges are also based on nonlinear THA with up to 6 sets of spatially variable input motions and the critical design quantities are taken from the maximum response encountered during any of the THAs. Each bridge system is based on a seismic design concept which clearly identifies sequential local inelastic hinges and a desired global seismic response mechanism where ductile behavior can be designed and detailed in the local hinges at locations where post-earthquake inspection and repair are possible without significant traffic interruptions. All other bridge components are protected against inelastic action through capacity design principles.

Check and Performance Validation: Finally an independent check and performance validation of the retrofitted bridges was required by Caltrans for all toll bridges the first time to be performed by a separate team utilizing a completely independent global nonlinear analysis model. In most cases even completely different analytical tools and programs were employed. This independent check and analytical validation of the retrofit measures was in parallel to a complete technical review by Caltrans of all retrofit designs, an independent evaluation by a Value Analysis (VA) team of all designs and their constructability, and an independent seismic safety peer review panel (PRP), which make the seismic toll bridge designs/retrofits some of the most heavily checked and scrutinized seismic design projects.

TOLL BRIDGE RETROFITS AND NEW DESIGNS

A few of the key seismic safety design/retrofit features for individual toll projects are highlighted in the following on examples of three toll bridge retrofits and one new toll bridge design.

a) Golden Gate Bridge: The Golden Gate Bridge was opened for traffic in May 1937 and is one of the most admired suspension bridges in the world. The overall bridge consists of a number of different structures and types which all have different seismic vulnerabilities, see Fig. 2, [Seim, et al, 1998].

Retrofit concepts for the Golden Gate Bridge largely focus on strengthening of substandard members and sections, such as strengthening of the main tower bases and the tower saddle/cable connections, to accommodate the increased seismic demands, but also local seismic response modification of sections of the bridge through the introduction of e.g. isolation bearing in the north viaduct and the addition of dampers in the suspension bridge between the towers and the superstructure.

b) Benicia-Martinez Bridge: The Benicia-Martinez Bridge was completed in 1962. It carries interstate highway I-680 over the easterly end of the Carquinez Strait between the cities of Benicia in Salano County to the north and Martinez in Contra Costa County to the south. The total length of the bridge is 1,896 m with approximately

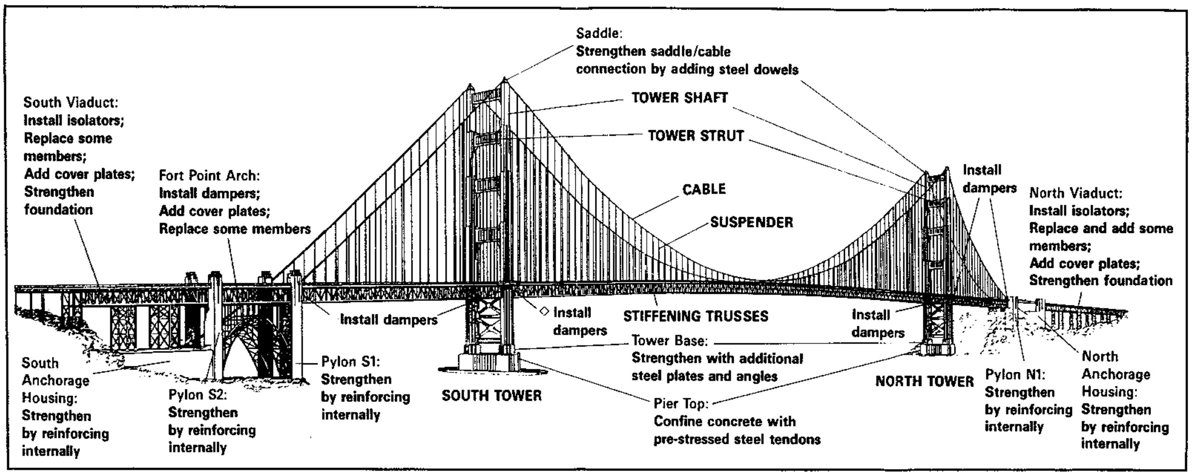


Figure 2. Golden Gate Bridge Seismic Retrofit Overview [Seim, et al, 1998]

1.5 km over water. The bridge is a high level, deck-type, welded truss with welded girder approach spans. Each truss section is 10 m deep. The highest span over the main navigation channel provides a minimum vertical clearance of 42 m above mean sea level. The over-the-water portion of the bridge consists of seven 161 m spans, two 131 m spans, and one 101 m span as depicted in Fig. 3.

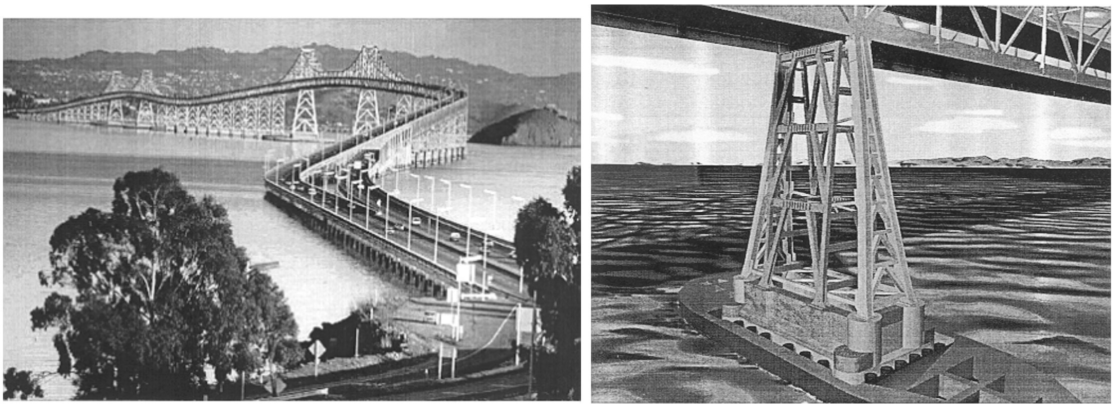
a) Bridge Overview b) Bearing Replacement

Figure 3. Benicia-Martinez Bridge Retrofit [PRP, 1999]

The retrofit design for the Benicia-Martinez Bridge is different from other toll bridge retrofit designs in that the designation as lifeline structure with immediate service following the SEE design event required special design considerations. Benicia-Martinez is the first long span bridge which is retrofitted by means of seismic isolation bearings with required displacement capacities of ±4 ft. Bearings which can accommodate these design displacements while carrying in excess of 6 million pounds of axial loads have not been built to date and their response characteristics have only been determined analytically. The isolated response period of the superstructure between 3.5 to 5 seconds also puts the seismic response in a range where very little information from actual recorded earthquakes exists. Thus, to base the seismic safety of a major bridge on such an isolation concept is a daring engineering solution which clearly expands the current state-of-the-art. A big step in engineering technology as proposed and designed for the Benicia-Martinez Bridge retrofit requires additional checks and validations of the proposed concepts and details to ensure the expected functionality. While the detailed analytical studies and independent checks all support the chosen retrofit concept, the isolation bearings themselves need to be fully tested and characterized as requested by the PRP and SAB to ensure that (1) bearings of this size can be manufactured to specification, (2) response characteristics of these bearings can be reliably achieved under design demands, and (3) response characteristics of these bearings will not change with time and environmental exposure. To provide these important bearing validations, a full-scale testing facility for seismic response modification devices (SRMD) is currently under construction for Caltrans at UCSD. Prototype bearings are also scheduled to be re-tested and characterized to the same test protocol after 5 year intervals to ensure time and environmental stability.

c) Richmond-San Rafael Bridge: The double-deck Richmond-San Rafael Bridge carries two lanes of traffic on each of its 11 m roadways across the northern end of San Francisco Bay. It was opened to traffic in 1956 and is one of the longest bridge structures in the United States with a length of approximately 4 miles, just slightly shorter than the San Francisco Oakland Bay Bridge.

The Richmond-San Rafael Bridge consists of two equal length double-deck cantilever structures with spans of 164-326-164 m approached and connected by 3,218 m of constant depth double-deck trusses. In addition there are 1,098 m of plate girder spans which transition from a single to a double-deck structure and a concrete trestle at the west end of the bridge.



a) Bridge Overview b) Anchor Pier Retrofit Details

Figure 4. Richmond-San Rafael Bridge Retrofit [PRP, 1999]

The most vulnerable elements in the existing Richmond-San Rafael Bridge are the existing bracings in the steel towers. The tower bracing will buckle under an earthquake that is less than the SEE and could result in the collapse of the structure. The strategy to prevent this from happening involves removing the bracing and constructing a ductile, eccentrically braced frame (EBF), see Fig. 4. The EBF's have sufficient stiffness at working load levels to resist wind and small earthquakes and are ductile enough to accommodate the maximum credible earthquake drift demands. The yielding of the shear links of the EBF's limit the demands on both the superstructure and the concrete substructure. This retrofit concept for the Richmond-San Rafael Bridge can be characterized as strategic subassemblage replacement with structural fuses to protect other vulnerable superstructure and substructure components.

New SFOBB East Bay Replacement Bridge: The new SFOBB East Bay spans consist of two parallel skyway or viaduct structures designed in variable depth precast concrete cantilever construction and cast-in-place deck and 14 spans of typ. 160 m each from the Oakland landing to a single structure cable supported signature bridge at the connection to Yerba Buena Island. The signature bridge is a self-anchored suspension bridge of 565 m length supported by a single eccentric pylon. The pylon consists of 4 hollow steel shafts connected in the transverse and longitudinal directions with replaceable shear links which are designed to yield in shear during the SEE event while the four tower legs remain elastic. The overall schematic seismic response system of the self-anchored suspension bridge in the longitudinal direction is depicted in Fig. 5, showing the location and types of actual hinges and expected inelastic local response mechanisms under the seismic input. The tower shear links represent sacrificial inelastic elements which provide energy absorption during and are replaceable after the seismic event. An overall view of the new SFOBB East Bay Bridge is depicted in the computer montage in Fig. 6.

Figure 5. SFOBB East Bay Bridge – Seismic Response Mechanism

Figure 6. Overview, New SFOBB East Bay Bridge (TY Lin, Moffatt & Nichol, J.V.)

CONCLUSIONS

In the design and retrofit of California's long span toll bridges, significant advances have been made to ensure safety and functionality. Advances consist of site specific hazard definitions which include source rupture mechanisms, rupture directivity, near source effects, pier specific soil conditions, and spatially variable input motion determination along the length of the bridge. Bridge design and retrofit are based on the critical response of multiple sets of 3 component nonlinear time-history analyses, and seismic design concepts utilize seismic response modification devices such as dampers, isolation bearings, or structural fuses to control displacements and limit structural force input.

REFERENCES

"Competing Against Time," Report to Governor George Deukmejian from the Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake, George W. Housner, Chairman, May 1990.

"The Continuing Challenge," Report to the Director, California Department of Transportation by the Seismic Advisory Board, George W. Housner, Chairman, October 1994.

"Seismic Soil-foundation-Structure-Interaction," Final Report by the Caltrans SAB ad hoc Committee on SFSI, Draft, October 1998.

Seim, C., Ingham, T., and Rodriguez, S., "Seismic Performance and Retrofit of the Golden Gate Bridge," Structural Engineering World Contress, San Francisco, 1998.

"Toll Bridge Seismic Safety Review" Report to Caltrans by the Toll Bridge Seismic Safety Peer Review Panel, Sacramento, CA, April 1999.