INSTRUMENTING THE GOLDEN GATE BRIDGE TO RECORD SEISMIC BEHAVIOR AND TO DEPLOY RAPID INSPECTION RESPONSE

Charles SEIM[1] And Mervin G GIACOMINI[2]

SUMMARY

The Golden Gate Bridge opened to traffic in 1937 as the longest span in the world. The facility is owned and operated by the Golden Gate Bridge, Highway, and Transportation District

After the Loma Prieta Earthquake in 1989, a Board of Inquiry was appointed by the Governor of California to investigate structural failures. One of its recommendations was to place seismic instrument on important bridges, including the Golden Gate Bridge, to capture their structural behavior under future seismic events. To comply, the District established a three-phase program..

Phase I: Installation of seismic instruments on the existing bridge and approach structures, and in bore holes, to record structural response and free field and down-hole ground motions. In July 1995, the Phase I bridge instrumentation was completed with an interim installation of 76 channels linked by telephone line to California's Strong Motion Instrumentation Program (CSMIP) headquarters in Sacramento, CA.

Phase II: After the retrofit construction, permanent instruments will be installed. An important feature will be the ability to validate any dynamic structural analysis program by comparing the calculated response to recorded performance.

Rapid Earthquake Response Plan: The District has also developed a Rapid Earthquake Response Plan (RERP). Beepers notify the District engineers who then initiate the ERP by assembling and deploying crews to critical areas of the bridge for a quick inspection of the general condition of the structure.

An important future development of the RERP will be to automate the method of notifying the District engineers of an event. The recordings from the instruments will be sent by telephone to CSMIP for signal processing and placing on the Internet. A dedicated computer, located at the toll plaza, will access the records from the Internet and perform a quick analysis of the recorded data and will determine critical bridge components needing a first-priority inspection.

INTRODUCTION

The Golden Gate Bridge is owned and operated by the Golden Gate Bridge, Highway, and Transportation District (District). The 2,790-m (9,151-ft) crossing consists of seven different bridge structure types. The South approach

contains a short section of steel girders, three simple span steel trusses varying from 38 m (125 ft) to 53 m (175 ft),

and a 97 m (320 ft) steel arch. The arch is supported on the bases of the two flanking concrete pylons. The most southern of the south pair of pylons is purely decorative. The north pylon supports the end of the side-span stiffening truss and houses a hold down system for the main cables.

[1] *Senior Principal, T. Y. Lin International, San Francisco California, 415 291 3700, cseim@tylin.com*
[2] *Senior Principal, T. Y. Lin International, San Francisco California, 415 291 3700, cseim@tylin.com*

The North approach also consists of a matching concrete pylon that also houses a hold down system for the main cables. This joins to a concrete anchorage housing, which protects the main cable anchors and supports the roadway deck. Five simple-span steel trusses of 53 m (175 ft) supported by braced, four-leg steel towers connects the North approach to the approach highway.

The all-steel main suspension bridge has a center span of 1280 m (4,200 ft), two side-spans of 343 m (1,125 ft) each, and towers that are 227 m (746 ft) tall. The seven bridge types are separated structurally but connected at the roadway level with expansion joints devices. The original seismic design used a static lateral load of 7.5 % of the dead load. [Strauss, 1937] presents a very detailed account on the planning, design, and construction of the bridge.

SEISMIC RETROFIT MEASURES

The Golden Gate Bridge lies 11 km (7 miles) to the east of the San Andreas Fault, which caused the M_s 8.25 San Francisco earthquake of 1906. The Loma Prieta earthquake also occurred on the San Andreas Fault on October 17, 1998. The epicenter of the magnitude 7.1 (M_s) event was approximately 100 km from the Golden Gate Bridge. The Golden Gate Bridge was not damaged by the Loma Prieta earthquake but other bridges in the San Francisco Bay Area were damaged and some were closed to traffic.

The District engaged T. Y. Lin International to evaluate the bridge to determine its seismic behavior and to develop retrofit measures under a major earthquake. Three design earthquakes were developed to be representative of a major earthquake on the San Andreas Fault. They are considered to be “maximum credible” earthquakes with a return period of 1000-2000 years. The seismic retrofit measures for the bridge used these design earthquakes as input.

The seismic retrofit of the bridge is intended to eliminate fundamental weaknesses, resulting from the original design of the bridge to an equivalent lateral force of only 7.5% of gravity. Some of the retrofit measures for the suspension bridge are the installation of dampers between the stiffening trusses and the towers of the bridge, replacement of one-quarter of the stiffening truss lateral braces with new ductile members, and stiffening of the bridge towers to prevent plate buckling. The retrofit measures also includes strengthening of the bridge piers, strengthening of the saddles that support the cables on the tops of the towers, strengthening of the wind-locks connecting the suspended structure and the towers, and strengthening of the pedestals supporting the orthotropic deck of the bridge. [Ingham, T.,et. al., 1995] presents a detailed discussion of the seismic retrofit design for the suspension bridge.

Retrofit measures for the approach spans include the installation of isolation bearings at the top of the steel braced towers, confining the concrete shafts of the south pylons in steel plates, and strengthening steel members and connections.

INSTRUMENTATION OF THE GOLDEN GATE BRIDGE

Immediately following the Loma Prieta earthquake, the Governor of California set up a Governor’s Board of Inquiry [Housner, G., et. al., 1990] to make recommendations for bridges and other structures. One of the Board’s recommendations was to install seismic instrumentation at the earliest possible time on the large bridges in the State, such as the Golden Gate Bridge.

To comply with this recommendation, a three-phase scope of work was established by the District for installing seismic instrumentation. The District also formed a Seismic Instrumentation Panel comprised of practicing engineers and professors to advised the District on the seismic instrumentation program. The seismic instrumentation was planned using the CSMIP [Shakal, A., F., et. al., 1995] for the rapid recording, signal processing, and disseminating medium.

(1) Phase I: Installation of seismic instruments on the existing bridge structure to record the structural response of the existing bridge and of the free field and down hole ground motions in the event of major earthquake.

(2) Phase II: Installation of additional seismic instruments, after the seismic retrofit of the bridge, to continue to obtain detailed information on the free field and down hole ground motions, on the structural behavior of the bridge, and on the effectiveness of the retrofit measures for the structure.

(3) Rapid Earthquake Response Plan: The District developed and placed in operation a Rapid Earthquake Response Plan to (a) notify key engineers by beepers of the level of intensity of the shaking and (b) a notification plan to assemble inspection crews quickly. An important future component of the response plan is to develop a method of locating critical bridge components for first-priority inspection, from a quick analysis by a dedicated computer housed at the toll plaza, of the effects of the recorded motion on the bridge.

THE PHASE I INSTRUMENTATION SYSTEM

The Phase I Seismic Instrumentation System consists of 72 accelerometers, 4 displacement sensors, and 2 recording stations. The distribution of the sensors is: (7) to the North Viaduct; (49) (45 accelerometers and 4 displacement sensors) to the Main Suspension Bridge; (14) to the South Viaduct; (3) in Down Holes; and (3) for Free Fields. The recording stations are located at the deck level inside the North and South Towers of the suspension bridge.

Locations of the accelerometers for Phase I were selected to quickly determine the structural behavior of the different bridge types. For example, on the suspension bridge, two orthogonal arranged accelerometers are mounted on the top of each tower, on the west side, to record horizontal activity. One additional horizontal channel is placed on the east side of each tower top to record longitudinal activity. The difference in responses between the two horizontal longitudinal records at the tower top, provides the torsional response of the top of that tower

Similarly, two vertical accelerometers are mounted at the centerline of the main span near each cable to record the up and down activity. The difference in response between the vertical records on the East and West side of the bridge provides the torsional response at the center of the main span. A single, transverse accelerometer records the horizontal activity at this same location. A single vertical accelerometer is mounted at the southern quarter point of the main span to record asymmetric torsional activity.

A similar arrangement is used at the center of the south side span, with a single vertical accelerometer installed at the center of the north side span.

For the South tower, instruments are mounted at the base, roadway level, and on the mid-height strut above the roadway. In a major event, the base of the towers will rock back and forth. This action will cause the steel base plate to rock up and down several centimeters on the concrete pier. Two displacement sensors are mounted at the south tower base and at the roadway level to record relative movements at these points. The same major event will cause the main-span stiffening truss to swing longitudinally toward and away from the towers. Large hydraulic dampers will be installed as a retrofit measure between the towers and the stiffening trusses to damp out the 'battering ram" action of the stiffening truss.

Data will be available for a careful and detailed study of the structural behavior after an earthquake large enough to significantly shake the structure and to trigger all the instruments (now set at 0.01 g). If the plan is successful, this post-earthquake study will validate the structural program and modeling, and will demonstrate the practicality of predicting locations on the structure for first priority inspection.

Individual channels are hard-wired to the recording stations in each tower. The recording stations are linked by telephone to the office of the California Strong Motion Instrumentation Program SMIP (Shakal, 1995) in Sacramento to transmit near real-time earthquake data. After a quick initial processing, these data can be sent back to the District in a few minuets via the Internet. In the future, the first-priority inspection plan will use this rapid information transmittal for a quick structural evaluation analysis, using a dedicated computer at the toll plaza.

The Phase I system was completed in July, 1995, and has been in good working condition since. The system has so far recorded only three minor seismic events, one on December 1995, centered about 17 km to the East, one on March 1997, centered about 23 km to the South, and the third in August 1999 centered about 25 km to the North of the bridge. These records prove that the system is working. However, all of these records show very low acceleration values and cannot be used to validate the structural program.

THE PHASE II INSTRUMENTATION SYSTEM

The Phase II Seismic Instrumentation System, containing 23 additional channels, will be installed in phases to coincide with the phases of construction of the seismic retrofit of the Golden Gate Bridge. These sensors will serve to obtain additional seismic data, and to capture the effectiveness of the new retrofit design measures.

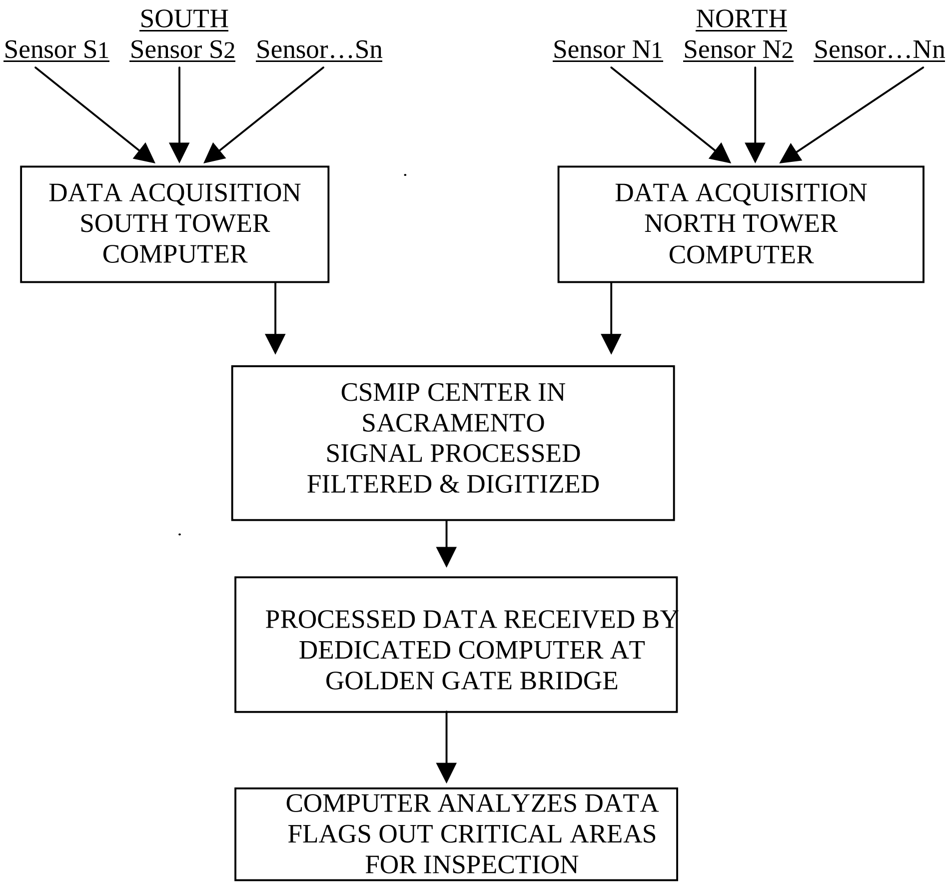
Some of the Phase I instruments will have to be removed to accommodate the retrofit construction. These will be reinstalled with additional channels after the retrofit is completed. The first construction contract of the seismic retrofit of the facility started in the summer of 1997 with the North Approach truss spans. The full retrofit of the facility is projected to be completed in 2004.

THE RAPID EARTHQUAKE RESPONSE PLAN

An important future addition to the Phase II Instrumentation System is the RERP, a rapid earthquake response plan to quickly deploy inspection personnel to determine the post earthquake condition of the bridge and its approaches. This plan is a logical outgrowth of making double use of the seismic instrumentation installed on the bridge. The plan was made possible by the development of near-real-time monitoring system of rapid data recovery and processing by the CSMIP [Shakal, A., F., et. al., 1995]

The estimated time to process the signal in the CSMIP headquarters in Sacramento is about one hour or less. This is about the length of time required to assemble inspection personnel many of who may have to come from a distant on earthquake-shattered streets or highways. The dedicated computer at the Toll Plaza building will retrieve the processed signals from the Internet and within minutes compare the recorded accelerations with preprogrammed values. The preprogrammed values will be determined from the same dynamic computer programs that were used in the analysis the structures for the retrofit design. Maintenance and inspection equipment and a communication center are housed at the Toll Plaza, which will function as a control center after a major event. Computers in the North and South towers function as data acquisition and sending units.

PROPOSED WARNING SYSTEM FLOW DIAGRAM



ACKNOWLEDGMENTS

The District established a Seismic Instrumentation Advisory Panel to plan and advise the District on the instrumentation systems. The Panel is Chaired by Prof. Emeritus Alexander C. Scordelis. Members are Charles Seim, P.E.; Prof. A. M. Abdel-Ghaffar; Prof. Emeritus Bruce A. Bolt; and Prof. Emeritus Ray W. Clough. Dr. Anthony Shakal, Director of the California Strong Motion Instrumentation Program, and Dr. Mark Ketchum serve as special advisors to the Panel. The District is represented on the Panel by Mervin C. Giacomini, P.E., District Engineer and Jerry D. Kao, P.E., District Senior Engineer, who worked diligently with the Panel and initiated the actual installation of the instrumentation systems.

SUMMARY

The Golden Gate Bridge is the first major long span suspension bridge to be fully instrumented with a near-real-time strong motion earthquake monitoring system. The approach spans structures will also instrumented. The first phase installation of the monitoring system was completed in 1995 and has recorded three minor seismic events. The permanent second phase will be installed in increments as the construction of the seismic retrofit for each contract is completed. The District will implement a rapid earthquake response plan to quickly assess any damage by Internet feed back from the recorded data by a dedicated on site computer.

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