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SEISMIC RETROFIT OF THE GOLDEN GATE BRIDGE

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ABSTRACT

The Golden Gate Bridge was completed in 1937 as the longest span suspension bridge in the world at that time. Today, it ranks as one of the world's most famous bridges and a symbol for the City of San Francisco. The Bridge is owned and operated by the Golden Gate Bridge Highway and Transportation District and carries six lanes of bi-directional traffic on State Route 101, linking San Francisco to the northern counties of California. The Bridge was not damaged by the Loma Prieta earthquake, being in an area of low recorded acceleration and having been seismically retrofitted a decade earlier to the then seismic standards. However, immediately following the earthquake, the District engaged T.Y. Lin International to perform a seismic evaluation for a much larger event. That evaluation found the Bridge likely to be severely damaged and in risk of collapse from a magnitude 8 earthquake on the San Andreas fault centered near the Bridge. A subsequent study of seismic retrofit concepts by T.Y. Lin International, indicated that the several structural types comprising the Bridge could be seismically retrofitted to the District performance criteria. The performance criteria required the Bridge to be immediately available for emergency vehicles and available for the use of the public a few days later, with a limited amount of repairs. This paper presents a description of the structural types comprising the Bridge, the site specific response spectrum and ground motions, architectural criteria, seismic design criteria and seismic analysis of retrofit measures. The conclusions are that retrofit measures can be developed, designed and constructed for the several structural types to provide adequate capacity to resist the damages from a major earthquake occurring on the San Andreas fault. Construction is scheduled to start in the Spring of 1996.

KEYWORDS: Golden Gate bridge, Seismic Retrofit, Loma Prieta Earthquake, Suspension Bridge, Steel Arch Bridges, Isolation, Dampers, Seismic Analysis, Bridge Architecture

INTRODUCTION

One of the most renowned bridges in the world, the Golden Gate Bridge opened to traffic on May 28, 1937. Today, it is a famous landmark bridge and stands as the very symbol of the City of San Francisco. The Bridge is owned and operated by the Golden Gate Bridge, Highway and Transportation District.

The Golden Gate Bridge was not damaged by the Loma Prieta earthquake. The bridge appeared to be in an area where the bed rock acceleration was recorded at about 0.08 of gravity. Immediately following the earthquake, the District engaged T.Y. Lin International (TYLI) to perform a seismic evaluation. In addition, TYLI performed concept retrofit studies and approximation of construction costs. The results of the seismic evaluation were presented in *The Golden Gate Bridge Seismic Evaluation* by TYLI in November, 1990 [1]. The evaluation revealed that a major earthquake on a nearby segment of the San Andreas or Hayward Faults would likely cause severe damage to the bridge. The *Golden Gate Bridge Seismic Retrofit Studies*, by TYLI in July 1991 [2], included development and evaluation of concept retrofit measures as well as estimation of their construction costs and schedules.

Currently, a joint venture between TYLI and Imbsen & Associates, includes: construction plans, specifications and cost estimates for seismic retrofit of the steel suspension spans and the northern approach, (which includes the steel viaduct) and the concrete anchorage and pylon. Sverdup Corp., is preparing the seismic retrofit construction plans specifications and cost estimates for the southern approach, which includes the steel viaduct, Fort Point Steel Arch, the concrete anchorage and pylons

BRIDGE DESCRIPTION

The Golden Gate Bridge was designed and built using the most advanced structural technology of the time, and until 1964, the bridge had the longest span of any structure in the world. The design and construction of the Bridge is well documented in the Chief Engineers Final Report [3]. The structural analysis theories that were used in the design of the bridge allowed a reasonably accurate evaluation of stresses and deflections under static dead load and traffic loads. They did not, however, accurately predict the response of the bridge to dynamic loads, such as wind and earthquake. For example, the bridge was designed for a seismic loading of only 7.5% of its weight and wind loading of about 50 psf. Only recently have analytical techniques become available to accurately calculate the dynamic responses of this type of bridge to wind and seismic forces.

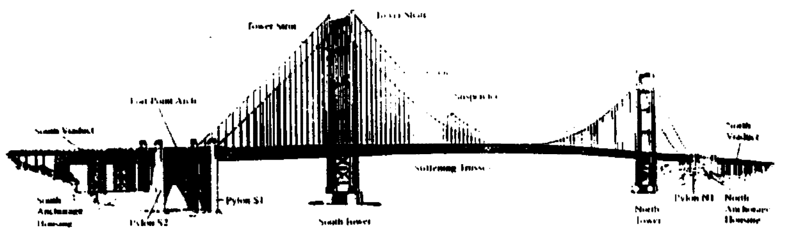

Figure 1

The 2,790m overall length of the Golden Gate Bridge consists of a number of different structure types as shown in Figure 1. The bridge's major components are the north and south approach viaducts, the 91m steel Fort Point Arch, the art deco concrete gravity anchorages and anchorage housings protecting the cable anchorages, the decorative concrete pylons and the 1,280m steel suspension bridge.
The Golden Gate Bridge has undergone several retrofit projects during its long life. A lateral bracing system was added as wind retrofit in 1954. Corroding vertical suspenders were replaced in the mid 1970s. The original concrete deck was replaced in 1985 with a lightweight orthotropic steel deck with a net reduction in weight of about 11,500 tons. The approach viaducts on the north and south were retrofitted with seismic restrainers in the early 1980s, following the California State Department of Transportation (Caltrans) recommendations at that time for Phase I seismic retrofitting. The Loma Prieta earthquake occurring at 5:04 PM on October 17, 1989, was rated at a magnitude of 7.1 and damaged buildings and bridges throughout the Bay Area. There is evidence that the devices functioned during the Loma Prieta earthquake and very well may be responsible for the excellent performance of the Bridge.

GOVERNOR'S 1989 BOARD OF INQUIRY.

Following the October 1989 Loma Prieta earthquake, the then California Governor appointed a *Board of Inquiry* to investigate the causes and effects of the damage sustained and to recommend methods to prepare for another major earthquake. The Board of Inquiry, chaired by George W. Housner, issued its reports, *Competing Against Time* [4], in May 1990. On June 2, 1990, the Governor issued an Executive Order D-86-90 which mandated State agencies to implement all the major recommendations of the Report.
A number of recommendations and findings of the Report are particularly pertinent to the evaluation and retrofit of the Golden Gate Bridge. The report and the Governor's Executive Order specifically refer to the vital importance of the Golden Gate Bridge and other toll bridges in the Bay Area transportation system because they are an "essentially nonredundant system" for transportation, in contrast to freeways.

SCOPE OF THE SEISMIC RETROFIT PROJECT

The purposes of initial First Phase studies commissioned by the District were to identify vulnerable areas of the various structures that comprise the Golden Gate Bridge. The second phase was to develop retrofit measures for these various structures, to prepare concept drawings, develop a preliminary cost estimate and construction schedule of the retrofit scheme. The Third Phase, now nearing completion, is the preparation of construction plans and documents.
These three phases required the evaluation of the seismic risk and generation of site-specific response spectrum and ground motions, development of performance and design criteria, applying computer models for seismic analysis including dynamic and inelastic techniques and finally, preparing contract plans and documents.

SITE SPECIFIC SEISMIC RISK, RESPONSE SPECTRUM AND GROUND MOTIONS

Seismic risk was evaluated by applying a probabilistic assessment of ground motion using the maximum expected earthquake values assigned to the two main faults, the San Andreas 7 km to the west and the Hayward 15 km to the east, with a magnitude of 8.3 and 7.3 respectively. The peak ground acceleration estimated for a maximum credible event comparable to the 1906 San Francisco earthquake was determined to be .65g.
The determination of site specific seismic risk, response spectrum and ground motions was based on the relative location of these nearby faults and the reoccurrence interval of the seismic event, and computer simulations of fault ruptures. The results of these studies were presented in *Geological, Geotechnical and Ground motion Studies for Seismic Retrofit of the Golden Gate Bridge*, in July 1992 [5].
Each of the three ground motions developed for this project contained multiple support excitation, proper estimates of incoherency for wave scattering and the traveling wave effects according to the measured wave velocity of the rock media below the bridge.

ARCHITECTURAL CRITERIA

According to the U.S. Historic Preservation Act of 1966 and the Secretary of the Interior's Standards for Rehabilitation, special consideration must be given to any changes to a bridge that may affect the design characteristics of the structure. For the Golden Gate Bridge, these include distinctive features, such as the steel arch over Fort Point, the flanking concrete art deco pylons and finishes like the International Orange color or 1930 type concrete striped form marks. If new work is required, it should not destroy historic materials that characterize the structure and should be compatible with mass, size, scale and architectural features to protect the historic integrity of the structure and its environment. These issues are not binding on the retrofit measures at this time, but were used as strong guidelines for the seismic retrofit design.
In recognition of these issues, the retrofitting measures developed to upgrade the seismic performance of the bridge will meet the following hierarchical guidelines:

1. First priority is meeting the seismic retrofit design criteria presented in the Design Criteria.
2. Maintain the current architectural appearance of the bridge and to follow as much as possible the guidelines of the U.S. Preservation Act of 1966. Preserve seismic retrofit measures as much as possible including the scale of member and proportions of solids to voids of the existing bridge.
3. Respect the architectural vocabulary established for each of the structural types comprising the bridge. Try not to radically change the character defining features, materials, finishes and color of the existing bridge.
4. Retain as much as possible of the original material that is now constructed into the structure.

DESIGN CRITERIA

The seismic design criteria for a retrofitted suspension bridge presents a compromise between available retrofit measures, constructibility constraints, user expectations and cost. Current American seismic codes are based on saving life but not necessarily saving the structure, however, the Golden Gate Bridge is a non-redundant link and toll facility. The retrofit measures for this structure must preserve life and allow the bridge to be used immediately after the largest expected event, first for emergency vehicles and then for the toll paying general public, in accordance with the Governor's Board of Inquiry [4] recommendations.

To guide the designers in developing the seismic retrofit measures of the Golden Gate Bridge, seismic performance criteria were developed by T.Y. Lin International [18], based on preserving the use of the bridge after a major earthquake with limited amount of repairs required essential elastic action.

The bridge structures were analyzed first in their current configuration, and not surprising, finding the structures would not meet the performance criteria. In fact, the structures were at risk of collapse. Retrofit measures were then developed to bring the structures into compliance with the performance criteria.

SEISMIC ANALYSIS AND RETROFIT MEASURES

The seismic analysis of the Golden Gate Bridge had two main objectives, predicting the vulnerabilities in its current configuration and evaluating the effectiveness of the proposed retrofit measures. The seismic response of the Golden Gate Bridge structures to strong earthquakes could be nonlinear due to large deformation effects and inelastic material behavior. The analysis did not try to predict the actual behavior under circumstances which should be avoided, such as collapse or loss of service.

Due to the complexity of the Golden Gate Bridge Structures, the seismic analysis was performed with a combination of global and local models. Several global models were developed for the four different structural types characterized by their distinct seismic behavior, such as the suspension bridge, the viaducts, the Fort Point Arch and the anchorage housings. Local models were developed for problem areas such as the base of the main towers, the horizontal struts between the tower's shafts and the base of the pylons. The seismic analysis of the various structures of the Golden Gate Bridge are well documented in References [6] to [17].

Suspension Bridge.

The characteristics of the suspension bridge which most significantly influence its seismic analysis are summarized below.

Large Displacement Effects and Multiple Support Excitation. Ground motion will be different at each of the widely spaced supports. The multiple support excitation analysis imposes relative displacements between the towers, cable hold-downs points within the north and south pylons and the concrete anchorage blocks that induce dynamic stresses. These analysis found only a minor increase, or in some cases a decrease, in the stresses in the structure, but the displacement of the expansion joints is generally larger.

Dynamic Characteristics. The suspension bridge has a long fundamental period of vibration that yields large displacements and lower seismic forces. However, higher vibration modes with a shorter period can make an important contribution. The analysis showed that the main cables and suspenders remain elastic.

The vulnerable areas and retrofit measures for the suspension bridge are presented in References [6], [9], and [12]. Briefly, they include:
1. Connection between Stiffening Trusses and Towers: Impact between the main span stiffening trusses and the towers as displacements exceed the existing displacement capacity. The retrofit measures include the installation of large capacity dampers at this location to disperse energy and limit displacements
2. Main Towers: Uplift due to rocking motion of the tower causes high contact stresses at the toe of the uplifting base, requiring strengthening of the steel plates to prevent buckling.
3. Concrete Piers: The piers supporting the main towers are subjected to high bearing stresses under uplift conditions. The installation of tensioned rock anchors around the top of the piers will provide confinement.
4. Cable Saddles: The connections of the cable saddles to the tower tops need to be strengthened for shear stresses due to differential cable tension.
5. Deck Panels: The connections of the orthotropic steel plate deck panels to the floor beams need strengthening.
6. Stiffening Truss: Install a new, larger, ductile upper lateral bracing system for the main span.

North and South Viaducts.
Many vulnerable elements were identified for the North and South viaducts, references [7], [15] and [17]. The vulnerabilities are: the concrete tower footings, the cast steel bearing shoes at the top of the towers which support the girder and truss spans, the gusset plate connections between the members in the towers, the vertical load carrying members in the bents and braced towers, several members in the truss and girder spans and the connections of the orthotropic deck panels to the floor beams.
The retrofit proposal for the viaducts includes: replacing the existing cast steel bearing shoes with seismic isolators, installing isolation deck joints, connecting each truss span to its adjacent span to transmit horizontal seismic forces, strengthening or replacing concrete footings replacing the steel towers with new compact tubular sections and strengthening the connections between the orthotropic steel deck panels and the floor beams with new support pedestals. Reference [15] presents more details on the South Viaduct.

South Pylons. The two South concrete pylons are both subject to overturning and non ductile cracking. The pylon closest to the water contains the main cable hold-down that must be safe-guarded in an earthquake to preserve the suspension bridge cable geometry. Retrofit measures include: providing common foundations linking both pylon legs, applying steel plates to both the outside and hollow inside to provide concrete confinement, circling the bases of the pylons with rock anchors to resist uplift, as well as replacing suspension side span rocker links and installing transverse large capacity dampers. Reference [13] provides more information on the seismic retrofit of the pylons.

Fort Point Arch.

The Fort Point Arch had several vulnerabilities. The four ribs of the arch will tend to lift off their bearings, which have no inherent uplift resistance, the arch rib members are subject to yielding, some secondary bracing members and connections are also deficient, as are the connections of the orthortropic deck panels to the floor beams.

The proposed retrofit measures for the Fort Point Arch include member strengthening, installation of new sway bracing, installation of energy dispersion devices, installation of bearing tie-downs, installing isolation deck joints and strengthening of the connections between existing orthotropic steel deck panels and the floor beams. Reference [14] presents more retrofit details and methods of analysis for the Fort Point Arch.

North and South Anchorage Housings.

The reinforced concrete anchorage housing have high ductility demands under seismic action, but they were built according to 1930s standards and they lack the necessary confinement reinforcements provide the needed ductility, as shown in Reference [16]. The proposed retrofit measures for the anchorage housings include installation of new internal framing, shear walls and footings, strengthening the existing outer concrete walls with steel trusses and providing hold-down resistance with footing rock anchors.

CONCLUSION.

The seismic retrofit studies have shown that retrofit measures can be developed, designed and constructed to provide adequate capacity to resist the demands from a major earthquake occurring on the San Andreas fault and comply with the recommendations of the Governor's Board of Inquiry. Contract plans and retrofit designs are nearing completion. The first construction contract, the seismic retrofit of the North Viaduct, is scheduled for advertising in March of 1996. The total construction period is scheduled to take five years.

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