Restoration and seismic strengthening of Colorado Street Bridge

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Abstract

In the first half of this century many significant concrete bridges were built in California. Preservation of these historic structures has become a challenge. The bridge elements are often severely deteriorated after years of environmental exposure and minimal maintenance, and the archaic materials are below the strength of modern materials.

Federal and State funding for preservation of these historic bridges automatically triggers a requirement for traffic load upgrading and for seismic retrofit. The bridges have to be brought up to modern standards while maintaining the distinguishing original quality of the structure and respecting the integrity of the original designer's structural concept. Interventions necessitated by the strengthening must be designed to maintain the historic appearance of the bridge.

The present technology for the preservation of historic concrete bridges in California is presented and the methodology is illustrated by a description of the restoration and seismic strengthening of the Colorado Street Bridge.

1 Introduction

Few of the historic concrete bridges in California meet current standards for traffic loading and they no longer have, what is today, an acceptable safety margin against seismic failure. Many early bridges were demolished but, fortunately, careful consideration is now given to restoration of these structures[2]. One of the most spectacular survivor is the Colorado Street Bridge in Pasadena near Los Angeles (Fig. 1). This concrete arch bridge was built in 1912 and it was the bridge

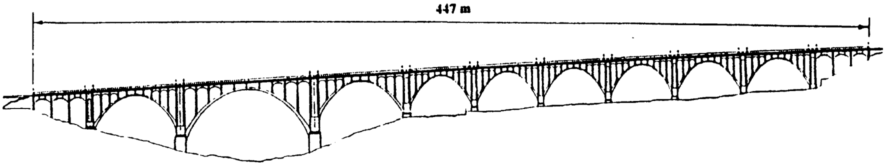

Figure 1: Colorado Street Bridge, Pasadena

of dreams on the way to Hollywood and stardom. The two-lane bridge served as the major connection between Pasadena and Los Angeles until the 1950's, when an adjacent bridge was built. Left with only minimal maintenance the Colorado Street bridge started to deteriorate. By the early 1990's the concrete showed severe cracking, softening of the cement paste and residue of leakage and efflorescence. The bridge arches exhibited extensive spalling and concrete delamination, particularly in areas where the concrete had been exposed to constant leakage. Reinforcing steel was exposed and steel area loss from corrosion was common..

The historic value of the bridge made it desirable to retain the structure and the State of California agreed to fund the restoration but only if the seismic resistance and the traffic load capacity were brought up to modern standards. The inspection and testing of the bridge elements and an assessment of the capacity revealed that the basic structure was sound but the original design had structural weaknesses and some of the reinforcing steel, especially the spacing of stirrups confining the concrete, was inadequate. The bridge had never suffered damaged by earthquakes, but an analysis suggested that it did not meet the current California seismic standards.

2 Bridge description

The Colorado Street Bridge in Pasadena near Los Angeles, California, is an open spandrel, eleven span arched concrete structure built in 1912-13. At 447 m long and 46 m above the bed of the arroyo, the stream channel below, it was the longest and highest concrete bridge of its time built in the United States (Fig. 2). The plan of the bridge is a horizontal S-curve and it features extensive decorative detailing and picturesque refuge bays set into the side railings on each pier.

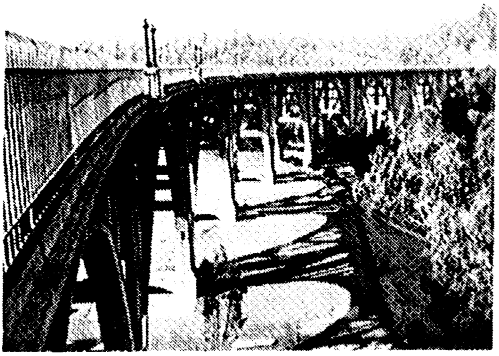

Figure 2: General view of Bridge

3 Field observation of existing conditions

Based on a document review of the bridge a close range inspection was conducted of all elements of the structure. The bridge deck was inspected visually and with a vehicle-mounted sound recording device to detect subsurface deterioration. Delaminations within the concrete slab at the level of the top reinforcing mat were recorded. The amount of delamination ranged from 33% to 93% of the surveyed deck area. The underside of the deck, spandrel columns, cross girders and high arch areas were surveyed from the bridge using a truck mounted "snooper vehicle" and from the ground using a high-lift crane (Fig. 3). The observed conditions, including delamination, concrete cracking, unusual displacements and performance of expansion joints were documented on design drawings. An assessment was also made of the soundness of the drainage system and of the operational capability of light standards and the ornamental bridge railing (Fig. 3).

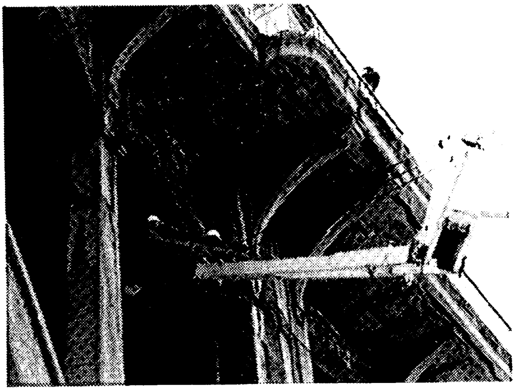

Figure 3: Field survey of bridge deck

Figure 4: Exposed reinforcing

Deterioration was observed throughout the structure. The concrete exhibited extensive cracking and delamination. Exposed reinforcing bars had steel area loss from corrosion. The bridge deck showed severe cracking, softening of the concrete paste and residue of efflorescence. The deck expansion joints were no longer functioning and the drainage system was defective. Rain water leaking through deck joints unto the concrete surfaces of piers and arches had caused severe delamination of the concrete cover and had exposed large sections of the reinforcing bars to corrosion. In many bridge members substantial steel area loss had occurred (Fig. 4).

4 Field and laboratory testing

It was important for the assessment and structural analysis of the bridge to obtain reliable knowledge about the condition and the strength of the existing materials. Cores removed from the structure were tested in the laboratory for concrete strength, permeability, durability, chloride content and level of carbonation. Field testing was used to determine if the reinforcing steel was actively corroding. Some of the concrete elements of the bridge are very massive and the compressive strength testing by use of concrete core samples was supplemented with impact echo testing. The advantage of this non-destructive technique is that many measurements can be taken faster and cheaper, the result reflects an average rather than a specific strength and the destructive effect of core drilling on the historic material is minimized.

Petrographic analysis of samples removed from the bridge indicated the cement content in the concrete was 270 kg/m^3 with a high water/cement ratio. The cement paste was exceptionally soft and the aggregate was very hard. The analysis showed a high depth of carbonation, ranging from 50 to 75 mm, a very low chloride ions concentration, and no evidence of micro cracking or alkali-silika reaction. The testing also showed the compressive strength of the concrete varied from 17 to 27 MPa.

The original concrete in the bridge has a warm tan color and it was installed with a wood board finish. The selection of repair materials and procedures was developed prior to the start of restoration work and it was verified on a series of large scale test panels at the bridge site.

5 Seismic strengthening and restoration criteria

The assessment and analysis of the existing structure indicated the bridge elements were severely deteriorated and the strength was below that of modern materials. The restoration strategy included a repair of the concrete deterioration, upgrading of the traffic loading capacity and a seismic retrofit to the level of present day standards.

The criteria for the restoration was based on the assumption that the historic material and features in the bridge were of primary importance. The work had to preserve the distinguishing original quality of the structure and respect, as far as possible, the integrity of the designers' original structural concept. The removal or alteration of any historic material should be avoided. Stylistic features, ornaments or examples of skilled craftsmanship had to be treated with sensitivity during the retrofit.

The traffic loading capacity had been lowered and the alowable trafic speed reduced as the bridge deteriorated over the years. The criteria for the retrofit was to upgrade the bridge to carry the US standard HS-20 highway traffic loading.

Federal funding for preservation of a bridge in California automatically triggers a requirement for a seismic retrofit. The design criteria for the seismic retrofit must be based on a deterministic evaluation of the maximum earthquakes that can occur at the bridge site[3]. The nearby faults are typically selected as the basis for the design earthquake and attenuating relationships are used to determine the best estimate of ground motion at the bridge site. The estimated "maximum credible" earthquake used in the design of the seismic strengthening of the bridge often has a rock acceleration of 45%g. The acceptance criteria developed by Caltran[4] limits the acceptable demand/capacity ratios for bridge members exposed to a "maximum credble" earthquake. The typical upper limits for the demand/capacity ratios in the design of some of the critical and non-critical bridge members are listed in Table 1.

Table 1: Seismic Analysis, Demand/Capacity Ratio

	Design Criteria
Arch rib moments, critical sections	**2.0**
Arch rib moments, other locations	**2.5**
Arch rib shears, critical sections	**1.0**
Arch rib shears, other locations	**1.0**
Column moments, crown columns	**4.0**
Column moments, other locations	**2.5**
Column shears, crown columns	**1.0**
Column shears, other locations	**1.0**

6 Retrofit strategy

The condition assessment and the preliminary analysis of the Colorado Street bridge indicated that the deck and the under deck cross girders did not meet current requirements for highway traffic loads and the deck would have to be replaced. The analysis also indicated that extensive seismic strengthening of the arches and piers was required. For the seismic retrofit the length of the bridge precluded that the seismic forces could be resisted by the end abutments. Therefore, each of the 11 spans had to be designed, seismically, as a separate structure, and the seismic forces would have to be brought to the ground through the arches and the vertical piers.

For the longitudinal seismic forces the arches became the critical sections, while in the transverse direction the seismic forces could be resisted by both the piers and the arches with the stiffer piers taking most of the load. The analysis indicated the arches had to be reinforced at the spring line because of the low compressive strength of the concrete, the small amount of reinforcing steel and the absence of effective concrete confinement. It was also necessary to increase the strength of the tall piers. Finally, the columns at the very top of the arches were found to be relatively stiff because of their short height and they attracted a disproportional amount of the seismic load. To reduce the seismic load, these columns had to be rebuilt with hinges top and bottom (Fig. 5).

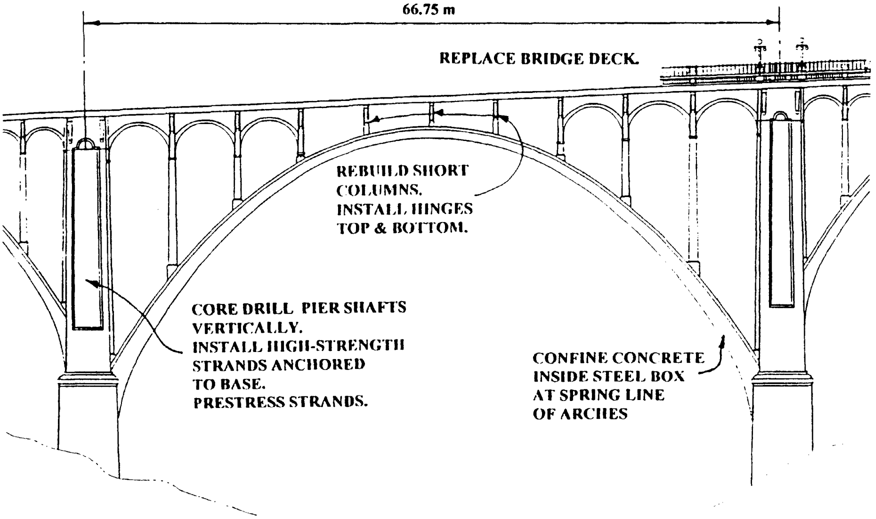

Figure 5: Rehabilitation and seismic strengthening

7 Structural analysis of bridge

The structural analysis started out with a model of the original structure. This model was then revised to account for the observed deterioration of the bridge elements and the tested strength of the materials. Gradually the model was modified to reflect the retrofitting required for the traffic load upgrade and the seismic strengthening. The final, retrofitted, model included the effect of rebuilding the bridge deck; reinforcing the arches at the spring line; strengthening the tall piers and pinning the short columns on top of the arches.

The seismic loading demand on the final model of the retrofitted bridge structure was determined from an M-Strudl analysis based on linear elastic methods. The more realistic non-linear behavior of the bridge during a severe earthquake was simulated by an iteration of the elastic analysis. In the final runs of the dynamic analysis the initial gross section (non-cracked) properties were modified for those members with a high demand/capacity ratio.

8 Preservation and retrofit

The preservation and retrofit consisted of a rehabilitation of the deteriorated concrete structure, strengthening of the bridge to current traffic load capacity and a full seismic retrofit. The work included the following features:

- The bridge deck was replaced. The original concrete was badly deteriorated, the strength was low and it would have required major modifications to strengthen the deck. The replaced deck is designed to meet current requirements for highway traffic loading. It matches the original appearance of the bridge deck and it incorporates the original railing and light standards.

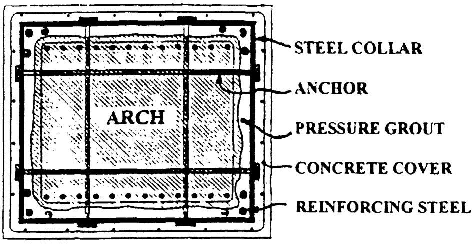

Figure 6: Concrete confinement at arches

The concrete arches are primary seismic resisting bridge elements. To increase their capacity the spring lines (bases) of the arches were reinforced with additional longitudinal steel and the concrete was confined by completely encasing it in a 6 mm steel collar. The welded steel collar was anchored to the original concrete and the in between space was pressure grouted. The steel collar was finally covered with concrete in order to match the original appearance of the arches (Fig. 6).

The piers are the main seismic resisting elements in the transverse direction of the bridge. The stiffness of the piers was increased by replacing the strut between the two pier shafts with a heavier reinforced concrete section. To strengthen the pier shafts 300 mm holes were drilled from the very top of the shafts all the way down into the base. Prestressing steel rods were then placed in the holes and anchored into the foundation. The holes were grouted and the steel was stressed. The prestress in the steel rods will prevent them from buckling during a quake, thereby avoiding the need for installing steel ties, which would have required intervention to the surface of the piers (Fig. 7).

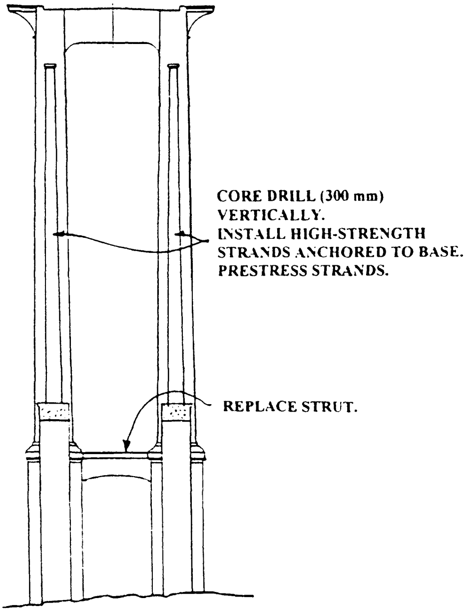

Figure 7: Strengthening of vertial piers

- The columns at the top of the arches were relatively stiff because of their short height and they attracted a disproportional amount of the seismic load. These columns were rebuilt with seismic hinges top and bottom.
- All exposed concrete was restored. Reinforcing steel bars, that had been exposed when the concrete cover spalled, were cleaned, coated with anti-corrosion paint and tied back to sound concrete, and the spalls were patched. The concrete for the restoration and for the replaced elements was carefully selected to match the warm color of the old bridge, and the original "form board" pattern was replicated by impressing the wet patches with pieces of lumber

9 Conclusions

The restoration and seismic strengthening of the Colorado Street Bridge preserved the original features and historical appearance of the structure, while extending its life span and bringing it up to today's standards for traffic loading and seismic safety. The retrofit and restoration strategy preserved as much as possible of the existing structure by repairing and strengthen elements rather than replacing them.

10 Acknowledgment

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11 References

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