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Seismic strengthening of historic concrete arch bridges

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Abstract

The most common historic bridge type in California is the concrete bridge. These concrete bridges have a distinct local imprint, the technology is innovative and the designers have placed great emphasis on the aesthetics. The most graceful are the concrete arch bridges, often located in the rugged wilderness of the State.[1]

Many of these historic concrete bridges show sign of deterioration due to corrosion or excessive cracking. They do not meet the current requirement for traffic loading and they no longer have an acceptable safety margin against seismic failure. The present technology for the preservation and seismic strengthening of historic concrete arch bridges in California is demonstrated in case studies. These include the Donner Summit Bridge, a fixed type open spandrel arch bridge in the Sierra Nevada, the Colorado Street Bridge, an eleven span arch bridge in Pasadena, and the Diestelhorst Bridge, a five span concrete arch bridge across the Sacramento River in Northern California.

Introduction

Californians introduced the concrete bridge to the United States, made many important innovations in concrete technology and built some of the most beautiful bridges found anywhere in the world. Owing to the high cost of steel bridges and the ready availability of high quality cement, concrete construction was economically feasible earlier in California than elsewhere. These concrete bridges were designed by Californians, the technology was innovative for its time and the designers placed great emphasis on aesthetics. Many of the surviving historic bridges match the rugged wilderness of the state, in the high Sierra Nevada, in the Sacramento River Canyon and along the Big Sur Coast.[2]

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The rapid growth of California and the love of the automobile have strained the usefulness of these historic concrete structures. Few of the bridges meet today's standard for traffic loading and structural safety. Many of the bridges have deteriorated due to the effect of weathering and traffic. Some structures were destroyed but today a careful consideration is given to preservation of a historic bridge before it is subject to demolition or ill conceived rehabilitation. The recent severe earthquakes have caused California to initiate a program to seismically upgrade the State's existing bridges. Preservation work on a historic bridge will automatically trigger the requirement for such a seismic retrofit.

Preservation of Historic Concrete Arch Bridges

The preservation of a historic bridge poses a variety of challenges for the design professional. The bridge elements are often deteriorated, the archaic materials are below the strength of modern materials, the traffic loading has to be upgraded, and the effect of earthquakes must be mitigated. And the retrofit work must preserve the distinguishing original quality of the structure and respect, as far as possible, the integrity of the original designer's structural concept. The removal or alteration of any historic material or distinctive architectural features should be avoided where possible and stylistic features, ornaments or examples of skilled craftsmanship should be treated with sensitivity during the retrofit.

Assessment of Existing Features and Structural Capacity

Preservation is based on the assumption that the historic materials and features in the bridge are of primary importance. To best achieve this goal, all available historic documents must be studied and the existing conditions of the bridge should be documented. A complete close up inspection must be performed in order to detect subsurface defects and concrete delamination. Field testing is used to locate areas of active corrosion and loss of steel section and material properties are established from laboratory analysis. The average property values for the concrete in the often massive bridge elements can be established by non-destructive testing such as pulse-echo procedures. The actual conditions observed during the inspection and the actual material values as established by the testing should be used as the basis for the structural analysis and the assessment of the bridge.

For some bridges, as seen in the case study of the Donner Summit Bridge, the assessment will show that repair of deterioration and localized modifications of the structure will be sufficient to prolong the life of the bridge, meet current standards for traffic loading capacity and provide adequate seismic safety. Other bridges, as seen in the case study of the Colorado Street Bridge, require major modifications in order to meet the standards for traffic loading and seismic safety. In some rare instances, as seen in the case study of the Diestelhorst Bridge, the assessment of the historic bridge will show it has sufficient strength and no retrofit is required.

Seismic Retrofit Criteria

The State of California requires that the design of the seismic retrofit be based on a deterministic evaluation of the maximum earthquakes that can occur[3]. The faults on which they occur are typically selected and attenuating relationships are used to determine the best estimate of ground motion. The design criteria will not reflect duration effects or velocity pulses, both of which could be important.

The demand on the as-built model of the bridge structure is typically determined from an M-Strudel analysis based on linear elastic methods. The non-linear behavior is simulated by an iteration of the elastic analysis where section properties of those members with a high demand/capacity ratio are modified to account for degradation.

The criteria for the demand/capacity (D/C) ratios of critical bridge members are:

Arch rib moment D/C ratio less than 2.0
Arch rib shear D/C ratio less than 1.0
Column moment D/C ratio less than 4.0
Column shear D/C ratio less than 1.0

The criteria for non-critical bridge members are:

Moment D/C ratio less than 2.5
Shear D/C ratio less than 1.0

Case Study - Donner Summit Bridge

Description

The Donner Summit Bridge is a 72 m long fixed type open spandrel arch bridge of reinforced concrete (Fig.1). It was built in 1925 at the top of the pass that is named after an emigrant party that partly perished when they were trying to cross over the Mountains into California during the winter of 1846. The bridge is located at the 2100 m elevation and the severe environmental exposure to moisture, freeze/thaw and road salting caused severe damage to several substructure elements. The damage progressed to the point where the bridge condition was rated poor and the traffic load rating was reduced.

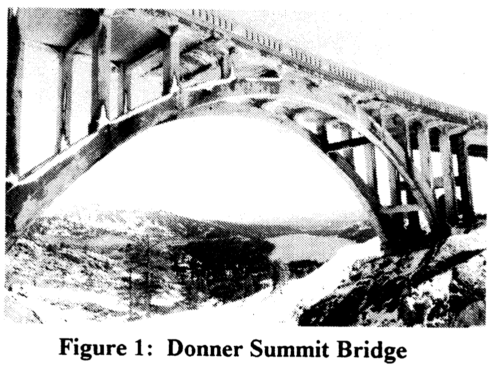

Figure 1: Donner Summit Bridge

Analysis of the bridge.

A close up field survey of the bridge and testing of samples from the original structure indicated that the basic bridge sections were in fair condition with no signs of structural distress, that concrete deterioration was confined to exposed sections and that the inside of the structure was sound. The concrete showed an absence of carbonation, chloride ions concentration was low, and the average compressive strength of the concrete in the arches was 36 MPa. The decision was made to rehabilitate this historic structure and this dictated a restoration of the concrete deterioration, upgrading of the traffic loading capacity and a seismic retrofit to the level of present day standards.

Seismic design criteria

The bridge is located about 4 km from a known earthquake fault. Two recent quakes of magnitude 6+ were centered about 30 km from the bridge and resulted in bed rock acceleration of 0,1g. The estimated "maximum credible" rock acceleration used for the design of the seismic strengthening of the bridge was 0,45g with depth to bedrock like material being less than 3 m at the bridge site.

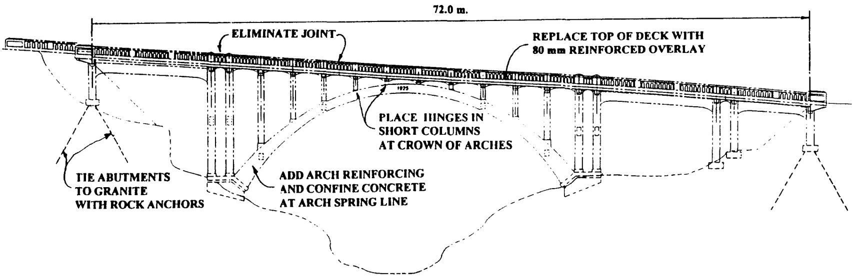

Figure 2: Donner Summit Bridge, Seismic Strengthening

Seismic strengthening

In the original bridge the arch structure was separated from the approaches by expansion joints and the deck had two additional expansion joints over the arches. These expansion joints not only were a source for the deterioration of the concrete but they also, structurally, divided the structure into five individual segments (Fig.2). The joints made the relatively weak arches become the main seismic resisting elements. To direct the seismic demands to the end abutments with their higher seismic capacity the following modifications were made to the structure.

1. The expansion joints were closed and an 8 cm reinforced overlay to the concrete deck provided a complete tie between the two end abutments.
2. The end abutments were tied with rock anchors to the granite base in order to develop additional capacity for longitudinal and transverse forces.
3. The arch ribs were modified at the spring line. Additional reinforcement and confinement of the concrete increased the capacity at these critical sections.
4. The very short columns at the crown of the arches were rebuilt with hinges top and bottom in order to reduce their stiffness.

Case Study - Colorado Street 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, it was the longest and highest concrete bridge of its time built in the United States (Fig.3). The bridge features extensive decorative detailing and picturesque refuge bays set into the side railings on each pier. The bridge was designed by Joseph Waddell, one of the nation's foremost bridge engineers, and built by John Drake Mercereau, a well known California builder.

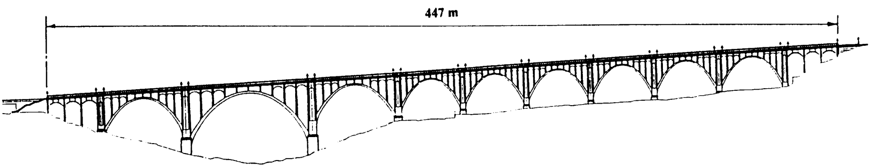

Figure 3: Colorado Street Bridge, Pasadena

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 bridge started to deteriorate. By the late 1980's the concrete showed severe cracking, softening of the cement paste and residue of efflorescence. The concrete 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..

Analysis of the bridge
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 and the load capacity was brought up to modern standards. The low strength of the concrete, 12,4 MPa, and the advanced deterioration in many elements of the bridge made the scope of the retrofit much more extensive than the retrofit of the Donner Summit Bridge. The assessment showed that the bridge deck and the under deck cross girders did not meet current requirements for highway traffic and the entire bridge deck had to be replaced. For the seismic strengthening it was clear that 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.

Seismic strengthening
In the longitudinal direction the seismic forces had to be brought to the ground through the arches. This made the spring line of the arches the critical section and the low compressive strength of the concrete made it necessary to reinforce

the arches. In the transverse direction the seismic forces have to be resisted by both the piers and by the arches with the stiffer piers taking most of the load. Their stiffness and the strength of the piers had to be increased. The retrofit of the historic bridge included (Fig.4):

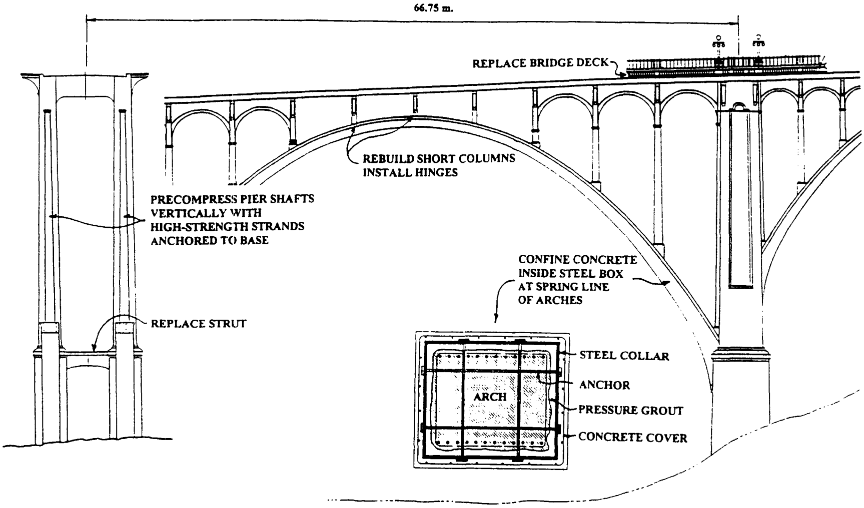

Figure 4: Colorado Street Bridge, Pasadena, Seismic Strengthening

1. The original bridge deck was replaced with new construction, matching the original in appearance, but designed to meet the current requirements for highway traffic.
2. The columns at the top of the arches were relatively stiff because of their short height and they attracted a disproportional amount of load. The columns were rebuilt with seismic hinges top and bottom.
3. The spring line of the arches was reinforced with reinforcing steel and the concrete was confined by completely encasing it in a 6 mm steel collar. The collar was anchored to the original concrete and the space in between was pressure grouted. Concrete was then applied to the collar in order to match the appearance of the arches.
4. The piers were the main seismic resisting elements in the transverse direction. The stiffness of the two pier shafts was increased by replacing the strut between the shafts with heavier reinforced concrete sections. To strengthen the pier shafts high strength steel strands were anchored to the pier bases and were then tensioned to precompress the shafts vertically.
5. All exposed concrete was finally restored, ensuring that the piers and the arches look exactly as the original bridge.

Case Study - Diestelhorst Bridge

Description

The Diestelhorst Bridge is a 195 m. long, five span concrete arch bridge across the Sacramento river in Northern California. The two-lane structure is 6,40m wide (Fig.5). It was built in 1915 as a replacement for a ferry crossing and it was the first concrete bridge to span the Sacramento River. During the construction and several times since the strength of the bridge was tested when the spring flood in the river reached the top of the bridge

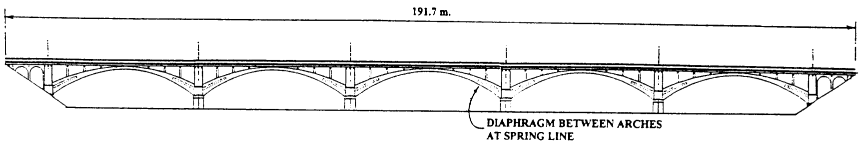

Figure 5: Diestelhorst Bridge, Redding, California

Analysis of the bridge structure

A close up field survey of the bridge showed that the abutments, piers and arches were structurally sound and without any serious signs of distress.. The original materials in the bridge were intact and only minor replacements or repairs had been made over the years. The cast-in-place concrete material was in good condition with no indication of alkali-silica or sulfate reactions and the compressive strength in the arches was around 26MPa. Some concrete spalling and minor delamination was in evidence and some reinforcing steel was exposed but the steel had only insignificant area loss from corrosion A stress analysis indicated that the bridge was capable of sustaining the current traffic load.

Seismic analysis.

The Diestelhorst Bridge is relatively solid compared to the light and elegant construction of the Donner Summit and the Colorado Street Bridges. It has heavy arches and it has massive piers filled with gravel and founded on bedrock. The structural elements are interconnected and in the plane of the bridge the seismic forces are resisted by the arches, the piers and the abutments. In the transverse direction the seismic forces are transmitted from the arches to the bridge piers and this transfer is greatly helped by the concrete diaphragm between the arches at the spring line. The piers are the main resisting elements. These piers were originally designed to withstand the force of flowing water when the river flooded the bridge. The loads imposed on the piers during a maximum earthquake are less than those from a fast flowing river.

Seismic strengthening

The deteriorated concrete was restored, but traffic loading capacity upgrade and seismic strengthening were not required for the Diestelhorst Bridge.

Acknowledgment

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