INNOVATIVE RETROFIT TECHNIQUES FOR SEISMIC RETROFIT OF CONCRETE ARCH BRIDGES OF EARLIER VINTAGE

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SUMMARY

This paper discusses seismic retrofit of a historic concrete arch bridge in California, USA. The retrofitted bridge has won Engineering Excellence Awards from American Consulting Engineers Council (ACEC) and Consulting Engineers and Land Surveyors of California (CELSOC). The Arroyo Quemado Bridge, constructed in 1916, is a historic twin arch concrete structure carrying the two southbound lanes of Highway 101, north of Santa Barbara, California. The as-built bridge structure was lightly reinforced and had non-ductile details. Seismic loading was not a concern during the design of the bridge. Analysis of the as-built bridge structure for seismic loads showed severe deficiencies in the arch ribs, spandrel columns, and approach bents primarily due to excessive lateral and longitudinal displacements. The retrofit solution focussed on limiting the demands and the retrofit requirements for the arch ribs. This was accomplished by improvement of the lateral load carrying system, which also helped control transverse displacements; provision of longitudinal restraints at the abutments to control longitudinal displacements and resulting demand; and provision of ductility capacity to those remaining elements undergoing substantial yield. Maintenance of the integrity and stability of the arches was central to the retrofit concept. Major considerations in the selection of final retrofit scheme included preservation of historic and aesthetic values of the bridge, constructibility, and environmental constraints.

INTRODUCTION

The Arroyo Quemado Bridge built in 1916 is a historic twin arch concrete structure, which carries the two southbound lanes of Highway 101, north of Santa Barbara, California, USA. The bridge is located in a zone of very high seismicity. The total length of bridge, including the approach spans, is 125 m (411 ft.). The bridge main span consists of two 33 m (109 ft.) long arch spans, as shown in Fig. 1.

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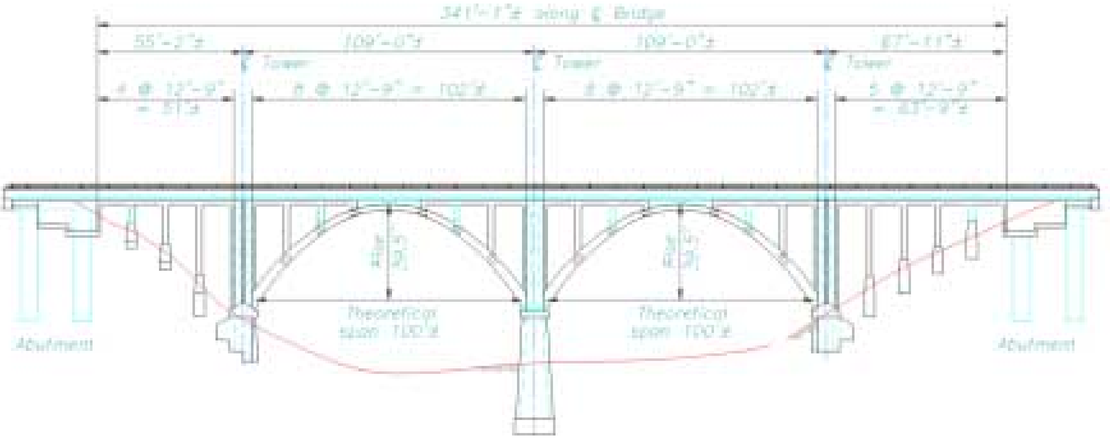

Figure 1 The Arroyo Quemado Bridge

The arch span structure is formed by two slender arch ribs connected by transverse rib ties, spandrel column bents (Fig. 2), and arch abutments. The load carrying system for the approach spans included a main tower at one end, an abutment at the other end and a number of intermediate approach bents. The bridge superstructure comprised a reinforced concrete deck, which was formed by slab and stringer-beam construction. The stringers and slab were cast integrally, and the stringers were of barrel vaulted form. The stringer beams assisted in transferring the design loads from the deck to the column bents of the bridge substructure. Expansion joints were placed at the abutments, main towers, and intermediate bent locations.

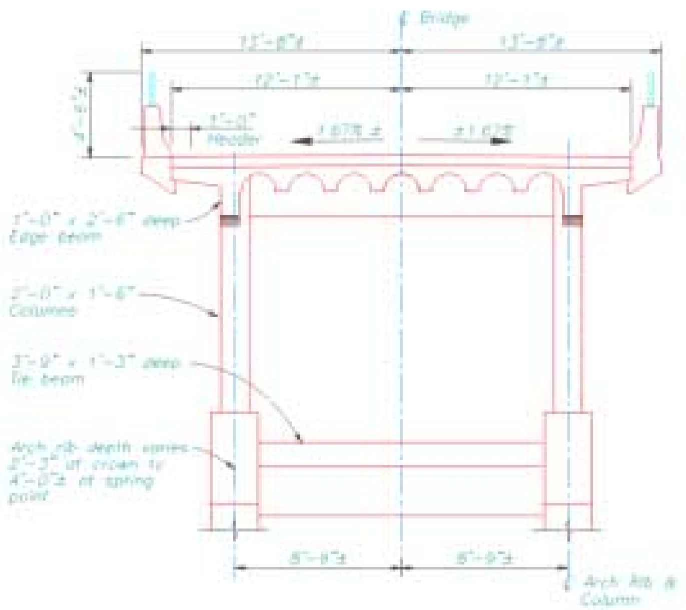

Figure 2 Typical Spandrel Column Bent

The scope of bridge seismic retrofit work included (1) assessment of the seismic performance of the bridge structure in its existing condition during the maximum credible design earthquake, (2) identification of weak links and inadequacies of the structure in withstanding the adverse effects of anticipated seismic event, (3) evaluation of alternate retrofit strategies, (4) analysis of the retrofitted bridge model to verify the structural adequacy against the design earthquake, and (5) preparation of the final detailed retrofit design. Constraints on the seismic retrofit strategy included respect for the historic and aesthetic qualities of the structure, retrofit constructability, and the need to minimize environmental impact on the site.

SEISMIC EVALUATION OF EXISTING BRIDGE STRUCTURE

Initial evaluation of as-built bridge structure showed that the bridge structure elements were lightly reinforced and contained non-ductile details. Gravity dead and live loads were the primary concern in the design of this bridge. As a result, elements and joints of the bridge structure were not designed and detailed to satisfy strength, stiffness or ductility requirements, as specified by the current design codes for seismic forces.

The most commonly encountered details in the bridge structure included (1) main reinforcing bars: square twisted bars (sometimes called Ransome bars after their inventor), (2) transverse reinforcement: smaller size bars, wider tie spacing and 90 degree hooks, (3) reinforcement development and splicing: inadequate development/lap lengths to develop reinforcing bar capacity and lack of confinement, as provided by transverse reinforcement, (4) joints formed by intersecting members: inadequate confinement reinforcement and poor detailing, and (5) member sizes which did not meet current code requirements on minimum dimensions.

DYNAMIC ANALYSIS OF EXISTING BRIDGE

A multi-mode dynamic analysis was carried out to determine the seismic demands on the various elements of the structure, including the arch ribs, arch rib ties, spandrel columns, tower columns, and abutments. The dynamic analysis was performed using an in-house structural analysis software, the Caltrans ARS spectrum applicable for the site (Fig. 3), and the Complete Quadratic Combination (CQC) technique for modal combination. The seismic forces were combined with the dead load forces to determine the total demand on each member.

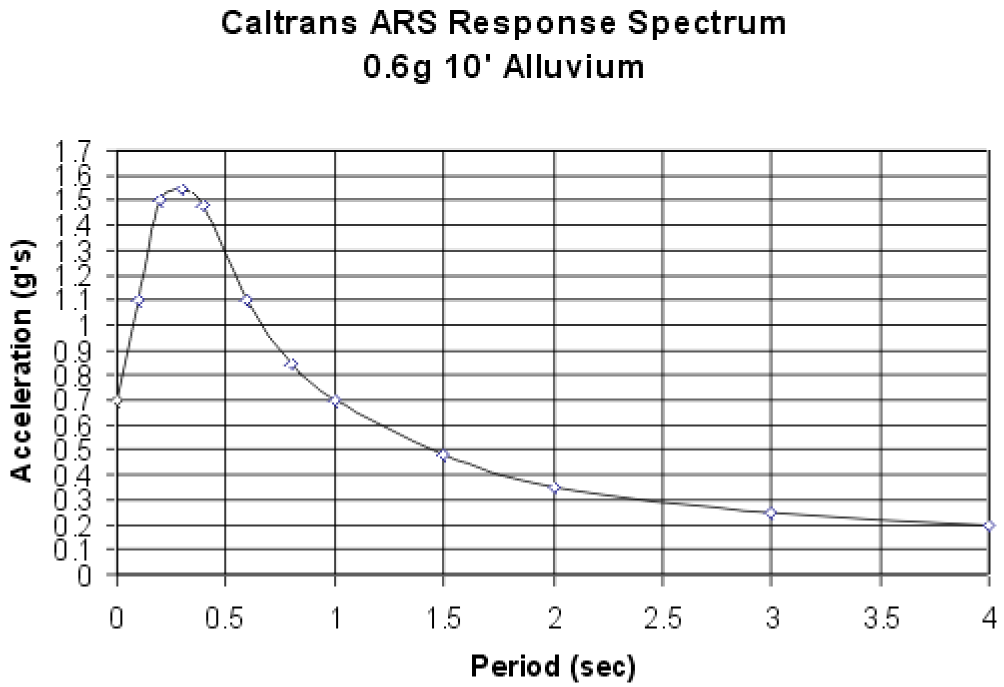

Figure 3 Caltrans ARS Spectrum for Bridge Site

Bending capacities for the structural elements were determined using a software package[7] which was able to account for the effects of axial loads and transverse confinement (or lack thereof). It was found that for low axial load ratios, P/f'cAg, experienced by the elements, the variation in moment resistance was a very nearly linear function of the axial load, hence, a representative linear relation was developed for each element.

As is common for reinforced concrete members, the Demand/Capacity, or D/C ratio is of the form M/Mr, where M is the applied moment and Mr is the applicable bending resistance at the given level of axial load. Hence, the effect of axial load is implicit in the bending resistance, unlike in steel members where an explicit P/Pr term is used. For biaxial bending, it would at first seem reasonable to express D/C as Mx/Mrx + My/Mry, where x and y refer to the axes of bending. However, this would imply that the frontier between Mrx and Mry (at a given level of axial load, P) is linear, where in fact, it is roughly elliptical, depending on the shape and aspect ratio of the member, and is perfectly circular for a round column (Fig. 4). Thus, a more realistic expression of D/C would be $\sqrt{((Mx/Mrx)^2 + (My/Mry)^2)}$, where Mrx and Mry are both functions of the applied axial load.

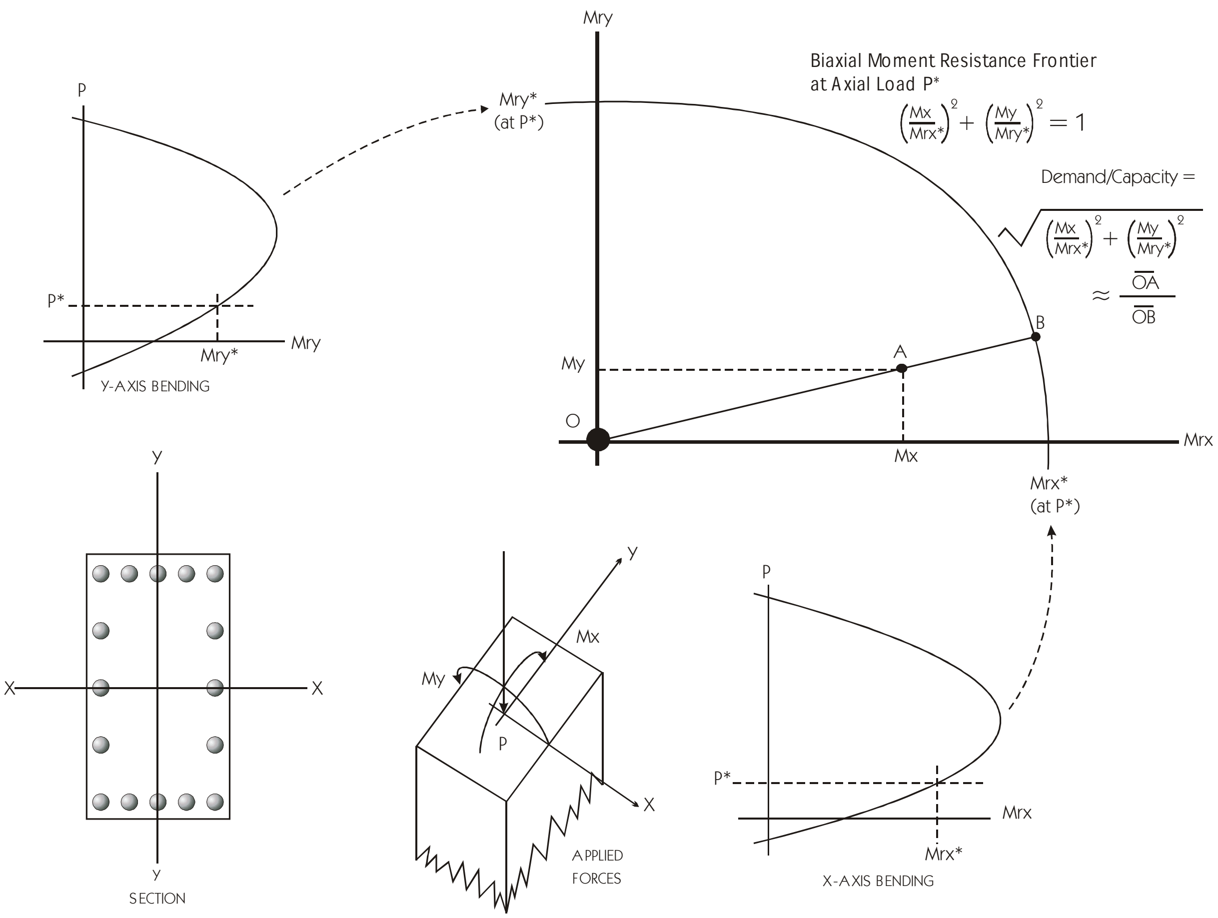

Figure 4 Biaxial Moment Resistenace Envelope For A Given Axial Load

Initial elastic modeling of the as-built structure indicated severe deficiencies in all members. D/C ratios for the critical arch ribs were in the range of 10, and the tower columns would be expected to snap in tension, due to failure of the reinforcing bars. Displacements were unacceptably large and it was found that, given the arch geometry, a 1-inch longitudinal displacement of the deck would result in a roughly 4-inch deflection of the arch away from the centreline. Analysis showed that computed longitudinal displacements of approximately 6-inches would result in severe arch displacements and lead to collapse of the arch system due to instability.

It was immediately recognized that the integrity and stability of the arches was the primary and central issue for the retrofit of this bridge. Initially, it was suggested that if the "secondary" elements, namely the spandrels and arch ties, could be given sufficient ductility and allowed to soften, then the forces on (and displacements of) the arch might be reduced. It was found, however, that the demands on the arches increased due to excessive displacements.

BRIDGE SEISMIC RETROFIT

Dynamic analysis of the as-built arch bridge structure and its observed behaviour led to the development of an innovative retrofit concept. Typical seismic retrofits are reactive, in that they provide the existing structural elements with sufficient strength and ductility to withstand anticipated seismic effects. However, for this bridge, (Fig. 5) the only viable retrofit option was a proactive re-engineering of the seismic load path.

An independent and effective seismic load path was inserted into the existing structure to limit the displacements and forces experienced by the arches. Transverse forces would be taken out through the deck and transferred to the towers and the abutments. Longitudinal forces would be taken out by the deck and transferred to the abutments. In order to accomplish this, the following retrofit measures were developed:

- Existing 6-inch asphalt paving was replaced by a reinforced concrete deck overlay (Fig. 6); expansion joints between the arch and approach spans and at other intermediate locations were eliminated to make the overlay continuous from the centre of the bridge back to the bridge abutments.

- Tower bases were strengthened with rock anchors, and shear walls were added between the tower legs to accommodate transverse forces (Fig. 7). Shear walls were then integrated with the new deck overlay.

- Massive reaction blocks on deep CIDH piles replaced abutments. The reaction blocks were then integrated with the new deck overlay.

This retrofit radically altered the stiffness characteristics and dynamic behaviour of the bridge, and ensured that seismic forces would be resisted mainly by the new load path, as opposed to by the arches in the as-built bridge structure. The dynamic model of the existing bridge structure was modified to reflect the proposed retrofit. Dynamic analysis of the retrofitted bridge structure model demonstrated that the selected retrofit scheme was effective, provided that the existing bridge structure elements meet the ductility demands in the retrofitted structure. Spandrel columns and approach bent columns of the retrofitted structure undergoing substantial yield were given the necessary ductility, using reinforced concrete jacket and epoxy glass wrap (Fig. 8).

Figure 5 The Arroyo Quemado Bridge Before Seismic Retrofit

Figure 6 New Reinforced Concrete Deck Overlay

Figure 7 Reinforcement For New Shear Walls Between The Tower Legs

Figure 8 Column Retrofitted Using Reinforced Concrete Jacket And Epoxy Glass Wrap

CONCLUSIONS AND RECOMMENDATIONS

This paper discusses seismic retrofit of Arroyo Quemado Bridge, a concrete arch bridge of earlier vintage. The retrofitted bridge (Fig. 9) has already attracted two Engineering Excellence Awards, one from American Consulting Engineers Council (ACEC), and the other from Consulting Engineers and Land Surveyors of California (CELSOC). Topics discussed include seismic evaluation of existing bridge structure, dynamic analysis of existing bridge, and bridge seismic retrofit.

Retrofit design methodology for concrete arch bridges located in high seismic regions should focus on limiting the member, particularly the arch, displacements on a global basis, and improving allowable material strain limits, if required, through local strengthening of members/joints. Maintenance of the integrity and stability of the arches should remain central to the retrofit concept.

Figure 9 The Arroyo Quemado Bridge After Seismic Retrofit

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