SEISMIC RETROFIT DESIGN GUIDELINES FOR PRE-1940 BUILT CONCRETE ARCH BRIDGES

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J. G. Wilson, P.E.[1], L. Panian, P.E.[2], D. S. Pajouhesh, P.E.[3]

Abstract

From the mid 1880's through the 1940's, many concrete arch bridges were built in the United States and throughout the world. The majority of these bridges fall into one of two broad categories: closed-spandrel arches or open-spandrel arches. These two types of arch bridges differ significantly in appearance and in the manner in which they resist gravity and lateral loads.

Recent design work has been done, by the authors, as part of the Caltrans Phase II seismic retrofit program. The work involved the retrofit design of 7 open-spandrel concrete arch bridges that were built along the central California coast between 1914 and 1940.

The need for a consistent methodology in determining retrofit strategies for these bridges became apparent and resulted in the creation of a set of guidelines that are summarized in this paper. These guidelines were developed specifically for open-spandrel concrete arches but should provide useful recommendations for the seismic retrofit of other types of arch bridges and even other types of structures.

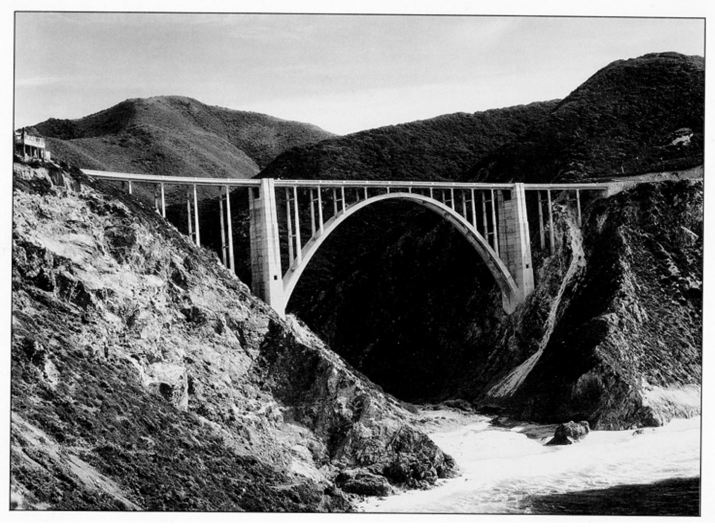

Fig 1. Bixby Creek Bridge

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1. Senior Engineer, Buckland & Taylor Ltd., 1575 Treat Blvd., #105, Walnut Creek, CA 94598, Phone: (510)472-8600, Fax: (510)472-8602
2. Engineer, Buckland & Taylor Ltd., Walnut Creek, CA
3. Senior Bridge Engineer, Caltrans, Division of Structures, MS9/EFPB, 1801 30th St., Sacramento, CA 95816, Phone: (916)227-8612, Fax: (916)227-8116

History of Pre-1940 California Concrete Arch Bridges

The advantages of arch bridge construction have been known for centuries. In fact, arch construction was understood by the Sumerians as early as 3200 B.C. The oldest surviving datable bridge in the world is a slab stone single-arch bridge over the River Meles in Izmir (formerly Smyrna) Turkey, which dates from c. 850 B.C. [ref 4]

Over the centuries advances in design methodology and materials science have enabled bridge engineers to continue increasing arch span lengths and reducing dead loads. Some of the most significant technological advances to influence U.S. arch bridge design were the invention of reinforced concrete in Europe, in the late 1840's, and the subsequent invention of twisted steel reinforcement bars by Californian E.L. Ransome.

Of the assortment of types of concrete arch bridges built in the United States between 1880 and 1940, the open-spandrel concrete arch bridge design is perhaps the most elegant and has resulted in some of the most notable historic bridges in the United States. One such bridge is the Bixby Creek bridge which was built in 1932 along State Route 1 on the rugged California coast near Carmel. One of the earliest open-spandrel arches, built in California, was the Buena Vista Viaduct (now called the North Broadway Bridge) in Los Angeles. The bridge was built by the City of Los Angeles in 1910 and incorporated sculptural detail designed by famed architect A. F. Rosenheim.

In 1897 the state Department of Highways was established and in 1911 was integrated into the California Highway Commission (later to become Caltrans). The Bridge Department group, led by Harlan D. Miller and his successor Charles E. Andrews, was comprised of a very talented pool of engineers. Both Miller and Andrews had high ideals relating to the aesthetics and architecture of bridge design. Between the two, they were responsible for the design of many of the State's open-spandrel arch bridges, most notably the series of early 1930's structures along State Route 1 between Carmel and San Luis Obispo.[ref 3]

Typical Features of California Open-Spandrel Concrete Arch Bridges

Arch

The arch typically consists of two (wider bridges may have more) slender prismatic arch rib elements connected by transverse rib struts. For long spans these arch ribs may be tapered. The reinforcing most commonly used are twisted bars. It is interesting to note that the European arches of this era used steel I-beam reinforcement (the "Melan System") or wire mesh reinforcing (the "Monier System"). Transverse reinforcing is typically nominal, such as ½ inch hoops at 24" o.c., for both arch ribs and rib struts. Fixed arches appear to be most common design; however, 3-hinged and tied arches were also built in this era.

Deck

Slab and T-beam construction are common. Expansion joints are typically placed at each bent or at alternating bents. Transverse beams may or may not be present.

Bent / Abutment Frames

There are basically two general types of bents: spandrel bents (supported directly on the arch), and approach bents (founded on soils). Spandrel bents are typically connected to the arch via dowels creating a lap-spliced region at the base of the columns. Approach bents are typically supported on spread footings or pile-supported footings. Transverse struts are used to provide transverse framing action. In order to accommodate thermal movements at the deck expansion joints, a split column detail was commonly utilized. The split is essentially an extension of the deck expansion joint which runs down the column a sufficient distance to give the column enough flexibility to accommodate thermal movement without exceeding strain limits. Transverse reinforcing for column and strut elements is nominal, such as 3/8" hoops at 12" o.c. Abutments are typically frames which are monolithic with the deck and similar in detail to approach bents.

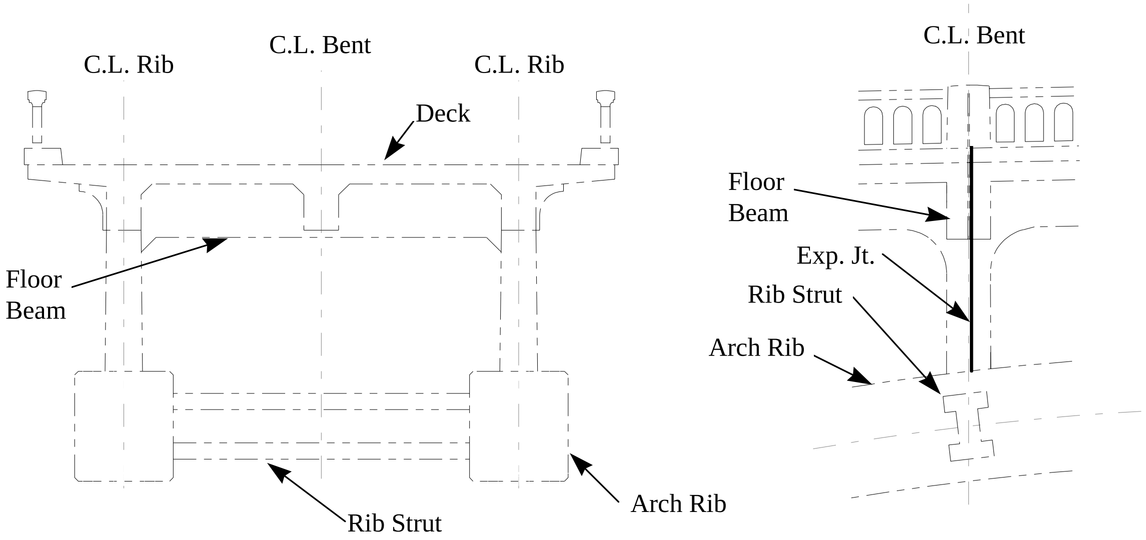


Fig 2. Typical Spandrel Bent

Performance Criteria

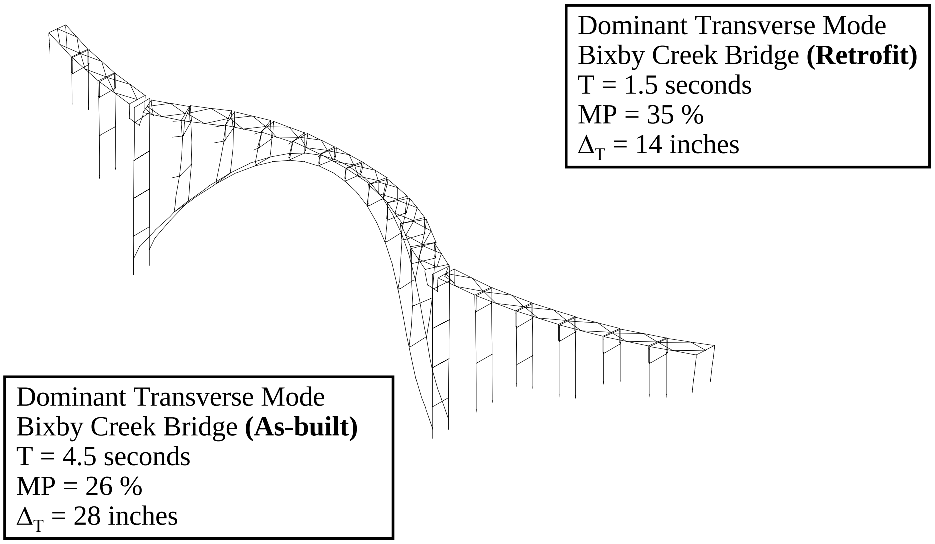
As a minimum, the seismic retrofit criteria should require that no collapse occur for the maximum probable earthquake over a given time period. The magnitude and return period of the design earthquake should be determined based upon the acceptable level of risk.

Inelastic deformations are tolerable to different degrees for different structural elements. To quantify and limit the amount of damage that would be sustained by various elements, limits on allowed strains should be established for individual member types based on expected failure modes. For example, since failure of the arch ribs would result in a global collapse it is logical that these elements should have the most stringent strain limit criteria. Also, strain limit values will vary for as-built versus retrofitted elements since available ductility and expected failure modes will differ.

Dynamic Structure Response

The dynamic response of open-spandrel arch structures are generally dominated by two distinct mass quantities, namely the masses of the deck and of the arch ribs. The dynamic interaction of these elements is complicated as they are coupled to one another and the foundation via bent frames which typically behave in a non-linear manner. If elastic analysis is performed to compute demands it must be recognized that the commonly used equal energy/equal displacement principle, which is based on elastic analysis of single degree-of-freedom systems, may not be reliable. An iterative secant-stiffness approach, which accounts for the progressive stiffness degradation of elements experiencing post-yield response, will give more realistic estimates of ultimate displacements.

Due to the inherent lateral flexibility of the deck and arch, the dynamic response of open-spandrel arch bridges is dominated by high period modes and characterized by large displacements. Deck expansion joints and split bent columns account for the deck flexibility. Arch ribs are typically connected by transverse rib struts and behave effectively like a long curved "Vierendeel" truss.



Dominant Transverse Mode
Bixby Creek Bridge **(Retrofit)**
T = 1.5 seconds
MP = 35 %
Δ_T = 14 inches

Dominant Transverse Mode
Bixby Creek Bridge **(As-built)**
T = 4.5 seconds
MP = 26 %
Δ_T = 28 inches

Fig 3. Dynamic Response (Bixby Creek bridge)

Demand Analyses

Determination of Global Displacement Demands

In lieu of a non-linear time-history analysis, it is recommended to estimate global inelastic deformations by elastic dynamic CQC analysis using an iterative secant-stiffness technique. A simple procedure for doing this is as follows: 1) Perform moment-curvature analysis for elements that could form a plastic hinge (this would include bent columns and struts, and rib struts); 2) Run the CQC analysis with elastic properties for all elements; 3) Tabulate $M_{CQC}/M_{PLASTIC}$ for all possible hinge locations; 4) Reduce the stiffness for the element with the largest $M_{CQC}/M_{PLASTIC}$ and rerun the CQC analysis; 5) Repeat steps 3 and 4 until the model has converged to its final softened state. In practice it may be expeditious to soften a group of elements at a time. Softening to achieve a precise value of $M_{PLASTIC}$ is not generally necessary since displacements are being sought, not forces.

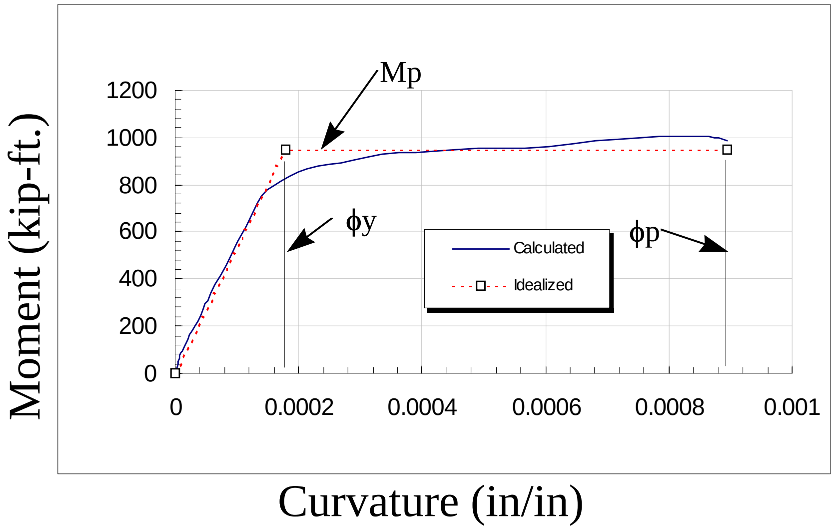
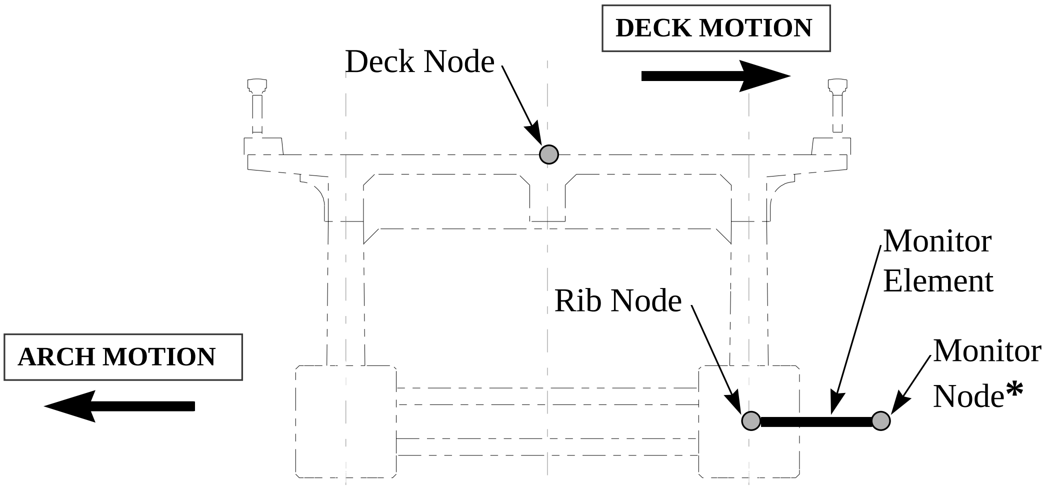


Fig 4. Moment Curvature Diagram

Determination of Strain Demands on Individual Elements

Once the displacement demands are obtained these deformations may then be imposed on individual elements (e.g. bents, arch ribs/rib struts and deck) in order to determine the resulting strains at critical locations. Strains may be determined by push-over analyses which consider non-linear material properties and P-Δ effects. The push-over analyses required for capacity determination will also yield the strain demand values.

For spandrel bent analysis, out-of-phase behavior between the deck mass and arch mass must be considered. To capture out-of-phase demands with a CQC analysis, monitor elements may be required, at each bent, that are attached to the arch at one end and slaved to the deck at the other end.



* Slave to Deck Node

Fig 5. Out-of-Phase Motion

Capacities

In order to determine capacities one must choose strain limits that are felt appropriate for a particular location. Since strains in the plastic regime indicate damage, it is important to identify critical lateral load resisting members, and provide limits which preclude excessive distress on these elements.

Care must be taken in establishing strain limits with due consideration given to materials, geometry, confinement and loading. Strain limits will differ for the as-built (non-ductile) and retrofitted (ductility enhanced) elements. Current codes offer little guidance with regard to strain limits, however much data has been generated in recent years from tests funded by Caltrans and performed at major universities in California, particularly UCSD.

There are some important element specific issues that must be addressed when performing capacity push-over computations:

> For 2-D spandrel bent analysis, boundary stiffness values at the arch rib - column base interface and at the deck, are difficult to estimate. A push-over may be done, with fixed base supports, to determine the bent capacity. This capacity is then compared against demands which include out-of-phase effects. Beam-column shear and joint shear may limit the bent displacement capacity and therefore must be checked.
>
> Arch push-over analysis may be done on a complete 3-D model with an applied inertial force or an applied displacement field which simulates the displaced shape for fundamental modes. In lieu of this, a simplified 3-D model consisting of only the arch ribs and rib struts may be used. The simplified model must have

boundary springs at the bent locations which account for the bent frame and deck stiffness. These stiffnesses may be adequately derived from an inertial push on the “softened” elastic model. It is particularly important to consider P-Δ effects for the arch ribs and bent columns since secondary effects, in some instances, have proven to be considerable.

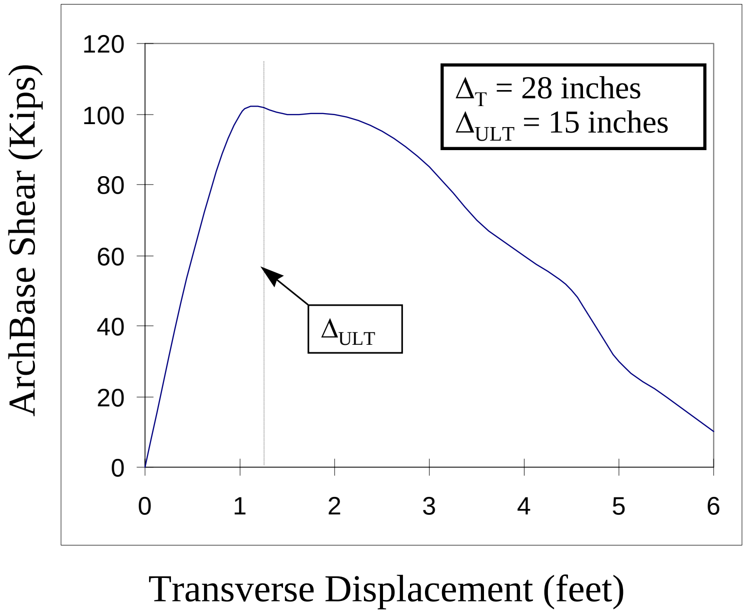


Fig 6. As-built Arch Force-Displacement Curve (Bixby Creek bridge)

The following strain limits were used for retrofit design of the Bixby Creek bridge [ref 5]:

Existing Concrete

f_c' = 4000 psi

Arch Ribs
ε_{cu} = 0.004 (unconfined)

Other Elements
ε_{cu} = 0.005 (unconfined)
ε_{cu} for confined/retrofitted concrete determined by Mander’s method.

Existing Reinforcing Steel

f_y = 33 ksi (twisted bars)

Arch Ribs
ε_{su} = 0.010 (unconfined)

Other Elements
ε_{su} = 0.015 (unconfined)
ε_{su} = 0.060 (confined/retrofitted)

Retrofit Design Considerations

The required degree of retrofit will of course vary from bridge to bridge depending on many factors including, magnitude of seismic loading, mass, geometry, etc.

Retrofit requirements for open-spandrel arches in areas of high seismicity tend to follow a similar pattern: 1) Limit the transverse displacement of the arch ribs; 2) Limit the transverse and longitudinal displacement of the bents/towers; 3) Resist the longitudinal deck forces at the abutments.

Limiting the transverse displacement of the arch ribs and bents can be achieved by adding continuity to the deck and linking the arch to the deck. Deck continuity can be achieved by addition of external unbonded tendons or other means. Where aesthetics issues are not a concern addition of bracing between arch ribs may be considered.

Longitudinal deck forces can be resisted by at the abutments by integrating drilled shafts into the existing abutments.

Where demand on non-ductile elements can not be reduced to a satisfactory level, confinement may be provided or the element may be fully, or partially, rebuilt. Care should be taken, in detailing, to avoid situations where rebar yield penetration could occur in primary gravity resisting members. This can usually be mitigated by adding haunches, pedestals or additional reinforcing at plastic hinge locations.

Finally, the designer must evaluate strength and serviceability conditions, where required, due to alterations of load paths in the retrofitted model.

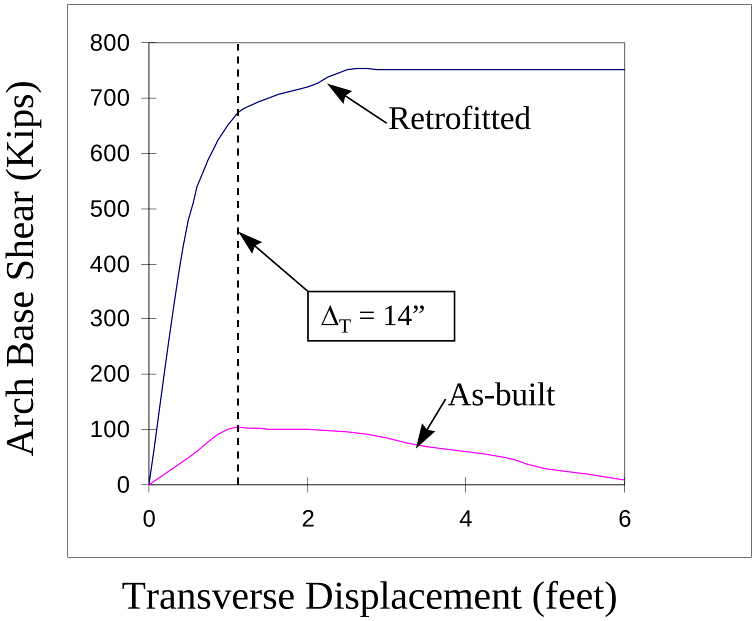


Fig 7. Retrofit Arch Force-Displacement Curve (Bixby Creek bridge)

Summary

Despite some of the peculiarities that are inherent to these 60 to 80 year old arch bridges, the same basic seismic retrofit concepts should be applied to these structures as would be applied to any other structure requiring seismic retrofit:

1) Provide a complete load path for transfer of all probable combinations of gravity and lateral loads,
2) Provide enough system ductility and local ductility to withstand the anticipated (cyclic) deformations.
3) Ensure that service conditions (thermal, live load, …) are not adversely affected by the retrofit design.

Because of the complex non-linear dynamic behavior of these structures, special care must be taken in evaluating seismic demands. Elastic analysis programs may be utilized to determine demands but a secant-stiffness approach should be performed since the equal displacement/ equal energy theories are not likely to be valid for these types of structures.

Damage criteria should be based on strain criteria rather than displacement criteria, since meaningful displacement capacities cannot be reliably computed for some elements, particularly the arch ribs.

Stability (P-Δ effects) of the arch ribs and bent columns should be evaluated by means of a program capable of assessing material and geometric non-linearities. A pushover analysis of the arch (isolated from the rest of the structure) by application of a displacement field representative of the dynamic motion will yield reasonable estimates of the strain demands on the arch rib and rib strut members and indicate if stability is a concern.

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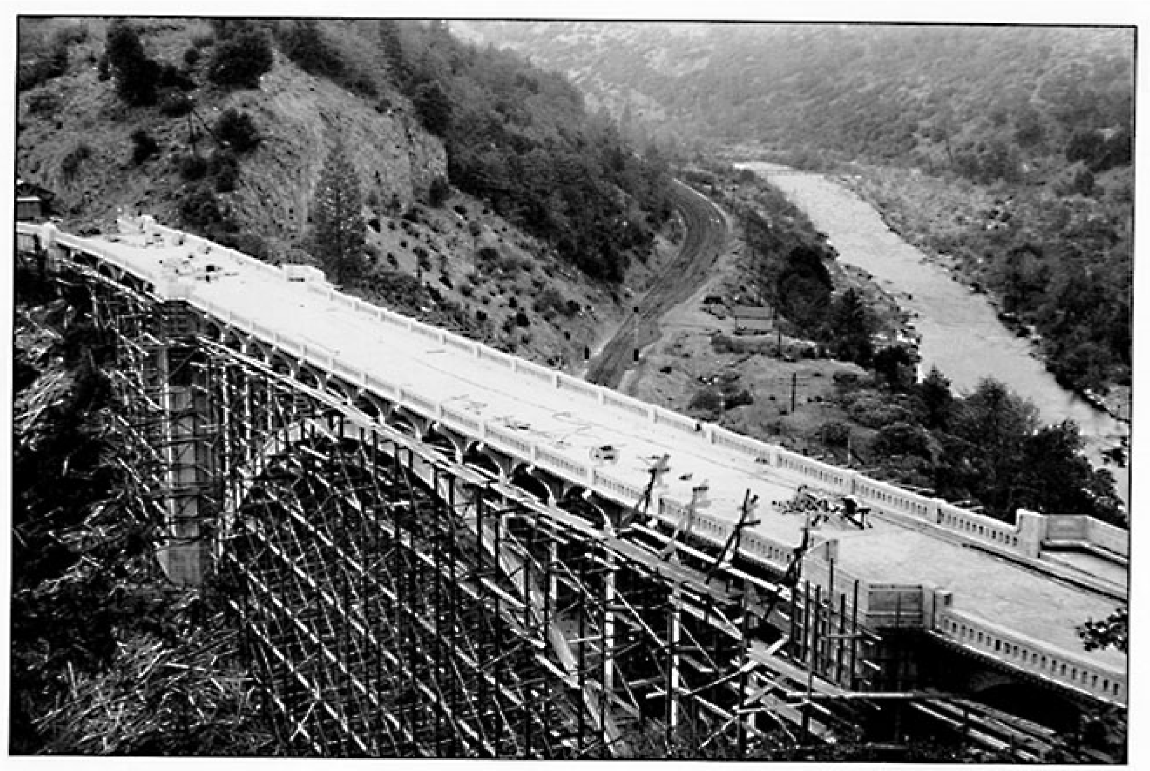

Fig 8. Harlan D. Miller Memorial Bridge (aka Dog Creek Bridge)
Under Construction in 1927

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