LRFD SEISMIC BRIDGE DESIGN, CALIFORNIA EXAMPLE

Mark S. Mahan[1]

Abstract

The newly approved AASHTO Guide Specification for LRFD Seismic Bridge Design (referred to as LRFD Seismic Guide Spec), July 2007, is greatly influenced by Caltrans' Seismic Design Criteria. In particular, the most critical Seismic Design Category "D", within the LRFD Seismic Guide Spec, has the same design requirements as in Caltrans' practice. It is expected that more of the California detailing of seismic-critical components will appear in other parts of US. The preferred California bridge system of Cast-In-Place Post Tensioned Box Girder Bridge has proven itself for many years; however, the Pre-Cast (PC) bridge systems in California are evolving. An example of a PC alternative with special seismic detailing is presented here.

Introduction

The AASHTO Guide Specifications for LRFD Seismic Bridge Design (referred to as LRFD Seismic Guide Spec) was approved in July 2007. In this document the US has been subdivided into four Seismic Design Categories A, B, C, and D. The state of California is mostly designated as Seismic Design Category D, or SDC D for short. It must be noted that the term SDC in the LRFD Seismic Guide Spec is different than the Caltrans' Seismic Design Criteria (SDC). The SDC D is the most demanding category within the Guide Spec and the requirements for this category are very similar to the Caltrans' SDC. All references made to one of these two codes imply that the other code is similar.

In Caltrans' seismic design practice all bridges are expected to meet three fundamental performance requirements of "Confinement", "Continuity", and "Balance". The LRFD Guide Spec has similar requirements that lead the designers towards the same outcome, particularly for LRFD SDC C and D. It could be argued that a major earthquake in California dictated each of these requirements from 1971 to present. Therefore, a brief review of three major earthquakes of 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge is presented in the next section.

The bridge design and construction practice has evolved from event to event. Some changes have come slowly and some have been very fast paced, due to public demand. Quick fixes have been obvious but some major changes have come slowly that one needs to search deep into Caltrans' practice to identify. A case study in a completed Pre-Cast project will be presented to highlight the slow changes and what may be coming in future.

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[1] Senior Bridge Engineer, California Department of Transportation, Sacramento, CA

Post Earthquake Evaluation of Bridges

It is a standard practice at Caltrans to dispatch a team of engineers to survey the damage following an earthquake and to prepare a report to include the lessons learned from that earthquake. The team is called Post Earthquake Investigation Team, PEQIT for short. The study of the three PEQIT reports following the earthquakes of 1971, 1989, and 1994 clearly shows their influence in seismic codes and practice of Caltrans.

The 1971 San Fernando earthquake revealed "Confinement" problems. Route 5/405 Separation structure, a two-span Cast-In-Place (CIP) post tensioned box girder collapsed due to the minimal confinement of No. 4 reinforcement ties spaced at 12 inches in the 4' by 5' rectangular columns. The rectangular ties were closed with a lap splice. The failure of this and several other bridges prompted Caltrans to use column cores with spirals and hoops. In addition, Caltrans installed cable restrainers for Pre-Cast and steel girders in conjunction with support seat enlargements.

The 1989 Loma Prieta earthquake proved that Caltrans needed to do more with the "Continuity" of structures. Massive failures, mostly on older bridges, questioned the entire Caltrans practice. The limited seat of only 5 inches for the San Francisco-Oakland Bay Bridge (SFOBB) caused the collapse of one segment of upper deck onto the lower deck. The old two-level Cypress viaduct with many pins in its structural system collapsed. The piles supporting the slab bridge near Watsonville sheared and punched through the deck. Even though the problem of seat width at intermediate hinges was identified in the 1971 earthquake, the lack of "Continuity" in the structural systems was one of the major findings of the 1989 earthquake.

The 1994 Northridge earthquake affected some older retrofitted bridges and some of the newer generation of bridges. At the I-5/SR-14 interchange lack of "Balance" was evident in the failure of the ramp. The column at bent 2 was much shorter than the columns at bents 3 and 4. The shear demand at bent 2 was extremely large causing a complete shear failure of this bent.

The experience associated to these major earthquakes is well reflected in the current Caltrans Seismic Design Criteria (SDC) and the LRFD Seismic Guide Spec.

Design Codes and Various Bridge Systems

A close study of Bridge Design Codes including the seismic codes reveals that the emphasis is on specific category of bridges. In other words, codes are written with specific bridge systems in mind. As an example, Caltrans' SDC is written with an emphasis on the Cast-In-Place (CIP) Post-Tensioned Box Girders. Most of the discussion regarding the "Confinement", "Continuity", and "Balance" assumes that the bridge has a ductile framing system. The LRFD Seismic Guide Spec has a list of

Earthquake Resisting Systems (ERSs) [table 3.3-1a] and Earthquake Resisting Elements (EREs) [table 3.3-1b]. This emphasis in the code is to encourage the design engineers to practice with proven components and systems. These lists have been carefully collected based on years of laboratory testing and post earthquake observations.

Expected Bridge Performance

Both Caltrans' SDC and the LRFD Guide Spec require "no collapse" for ordinary standard bridges. This is a very simple performance criteria because the more complicated bridge performance criteria requires bridge specific laboratory testing which is only justified for special bridges. California Toll bridges each have their own performance criteria, which include "Safety" and "Functionality" definitions.

A closer look at the list of all EREs mentioned above and a study of the latest seismic design practice shows that only a certain combinations of EREs are placed in a specific bridge. For example, Plastic Hinges in columns and shafts are not usually mixed with the isolation devices and energy dissipaters. On the other hand, the abutment backfill soil can be mixed with any other ERE. Some ERE's are preferred for new bridges and some are preferred for old bridges. Rocking of the bridge foundation is very rarely used in new bridges and it is mostly appropriate for retrofit strategies.

Caltrans' Preference of EREs

As mentioned earlier, Caltrans has adopted the Plastic Hinges (PH) in columns and shafts as the main ERE with the abutment backfill mobilization as the preferred ERS in Ordinary Standard bridges. This is clearly different than other States within the US where Pre-Cast systems are in abundance. This choice is based on many component testing of columns performed by various universities for Caltrans, following the 1989 Loma Prieta earthquake. Figures 1, 2, and 3 show the deflected shape of the column and the condition of the PH for the 6' diameter column/shaft test at UCLA. Similar columns are expected to perform to drift levels well beyond 5% in a bridge.

Many design engineers at Caltrans use the column/shaft combination to design bridges similar to the bridge shown in Figures 4. Multi-column bridges supported on shafts also add an element of redundancy and enhance the seismic performance of the bridge by providing two Plastic Hinges per column/shaft. This doubles the energy dissipation capacity of the bridge (see Figure 5).

Seismic Performance of Pre-Cast Bridge Systems

In traditional Pre-Cast (PC) bridge systems the PC girders are stacked on top of the substructure and the bridge does not have the same robust framing characteristic as in the Cast-In-Place (CIP), Post Tensioned bridges. The problem typically is present at the sub-structure to super-structure interface. PC girders are placed on top of the bent cap beams and the bridge does not resist bending moments in the longitudinal direction.

For a long PC bridge supported on single-column bents the engineer must identify a proper ERS requiring a fixed-based column. Such sub-structure is comparable in cost to the CIP bridges. However, for a long PC bridge supported on multi-column bents the engineer needs fixed-based columns, while a CIP bridge can perform well with pin-based columns. The cost difference between the two systems is considerable, indicating the advantages of the CIP system. Therefore, CIP and PC alternatives are not equal in many situations; however, the project engineer is required to provide equal performance.

Given all of the above considerations one design team at Caltrans designed a PC system to compete with CIP, particularly in regards to seismic response of this major structure described below.

San Mateo – Hayward Pre-Cast (PC) Bridge

A 4.46-mile portion of the San Mateo - Hayward Bridge (see Figure 6) was designed as mostly PC elements crossing the San Francisco Bay. This is the low-rise segment of this major bay crossing. The design engineer provided several options, from which the contractor bid on the 42-inch PC shell piling with 90-foot PC girders, mixed with partially PC bent cap beam and partially PC deck.

Initially, three 42-inch diameter PC shell piles where driven through the bay mud to obtain adequate bearing with cut-offs at proper elevation above water (see Figure 7). Then collars were placed around each pile at the top to support a partially PC "bath tub" cap beam (see Figure 8). Partially PC bent cap beam (Figure 9) was supported on the collars (Figure 10) at proper elevation. Then the longitudinal girders were placed in bent cap beam cavities (see Figures 11, 12 and 13). The bottom steel extending from the girder ends were connected using mechanical couplers (see Figures 14 and 15) to provide the continuity and framing action in the longitudinal direction. Reinforcement cages were placed in the hollow pile extensions to frame them into the cap beam. Then concrete was poured into the cap beam simulating a CIP construction (see Figure 16). Later, the longitudinal deck reinforcement would complete the column-cap-girder framing as if all were a part of CIP system (see Figure 17).

With all complexity to this PC Bridge design the contractor was able to build 270 feet of bridge per week (see Figure 18). The additional complexity of this bridge system should be judged relative to the enhanced seismic performance of such system.

Conclusions

Seismic design codes have been traditionally updated due to major failures following devastating earthquakes. The Caltrans' Seismic Design Criteria has been improving through three decades of seismic practice and it has greatly influenced the national LRFD Seismic Guide Spec.

Seismic codes are usually written with specific seismic bridge systems and components in mind. The Cast-In-Place, Post-Tensioned Box Girder bridges are the primary choice at Caltrans with Plastic Hinging in columns and shafts. The abutment soil could be used as a energy dissipating mechanism. The LRFD Seismic Guide Spec includes these elements in addition to a more comprehensive list of specific Earthquake Resisting Systems (ERSs) and Earthquake Resisting Elements (EREs).

Pre-Cast (PC) bridge systems can be detailed, at an extra cost, to simulate the CIP systems under seismic demands. Such PC systems have higher component cost and demand longer construction schedules. However, It is estimated that the post-earthquake repair cost will be lower and they could be back in service faster.

References

- AASHTO Guide Specification for LRFD Seismic Bridge Design (LRFD Seismic Guide Spec), July 2007.
- California Department of Transportation, Caltrans Seismic Design Criteria, SDC version 1.4, June 2006.
- California Department of Transportation, The San Fernando Earthquake, Field Investigation of Bridge Damage, 1971.
- California Department of Transportation, The Loma Prieta Earthquake, Post Earthquake Investigation Team (PEQIT) report, October 17, 1989.
- California Department of Transportation, The Northridge Earthquake, Post Earthquake Investigation Team (PEQIT) report, January 17, 1994.

Conversion Table

1 mile = 5280 feet
1 foot = 12 inches
No. 4 US Reinforcement = No. 13 Metric Reinforcement
1 inch = 25.4 mm

FIGURE 1 - SIX-FOOT DIAMETER COLUMN/SHAFT TEST AT UCLA.

FIGURE 2 - PLASTIC HINGE BELOW GROUND.

FIGURE 3 - HOOP FRACTURE AT MAXIMUM DUCTILITY.

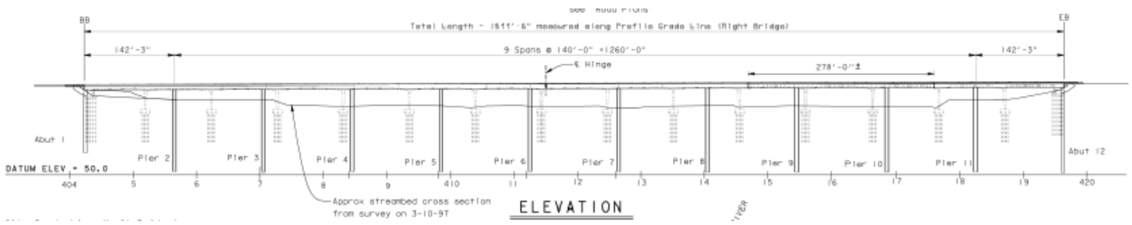

FIGURE 4 - SALINAS RIVER BRIDGE, 1550-FOOT CAST-IN-PLACE POST TENSIONED BOX GIRDER BRIDGE.

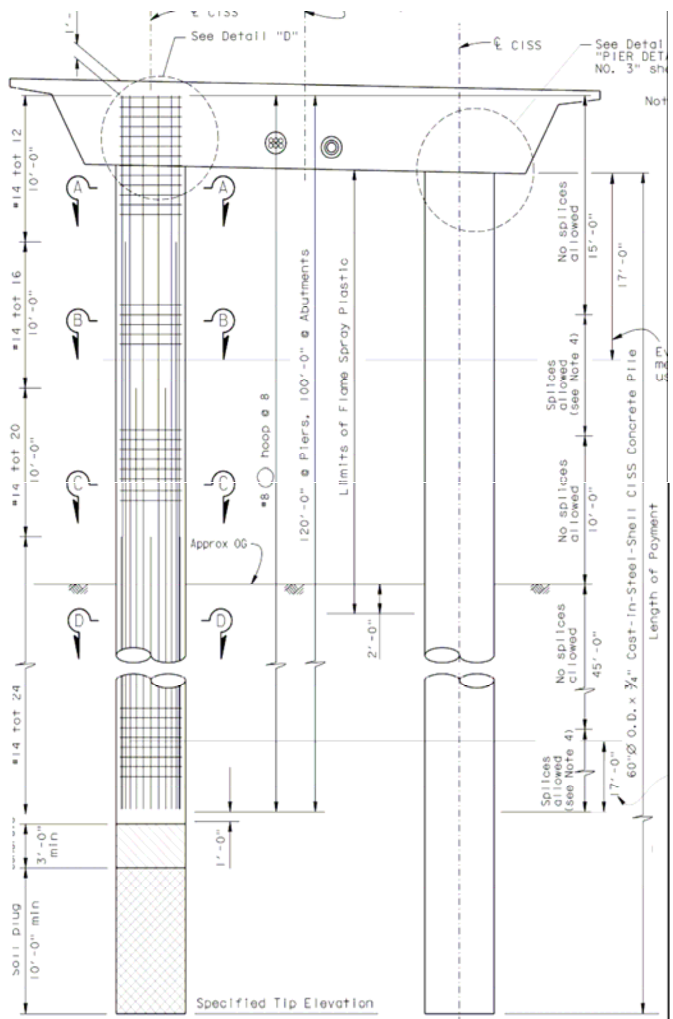

FIGURE 5 – TWO-COLUMN BENT SUPPORTED ON SHAFTS.

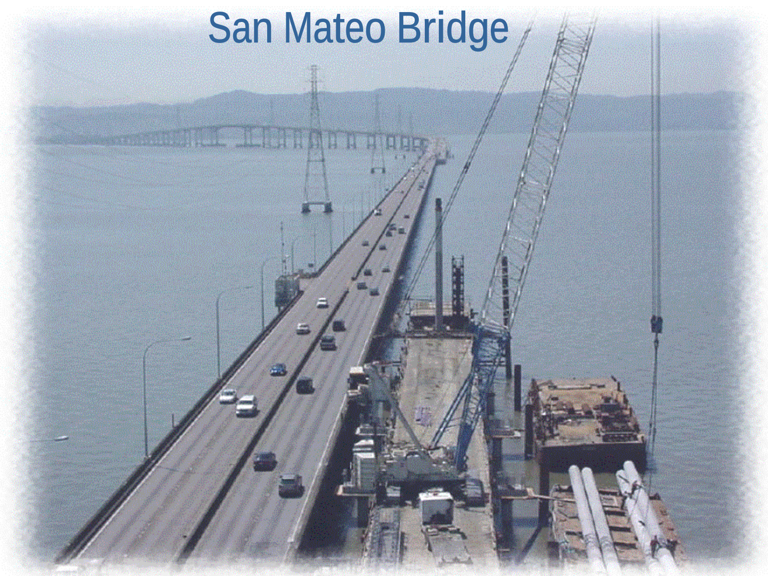

FIGURE 6 – SAN MATEO – HAYWARD BRIDGE.

FIGURE 7 - 42-INCH HOLLOW SHELL COLUMN/SHAFT DRIVING OPERATION.

FIGURE 8 - COLLAR PLACED AT TOP OF COLUMN TO SUPPORT PRE-CAST BENT CAP BEAM.

FIGURE 9 – PRE-CAST PORTION OF THE BENT CAP BEAM.

FIGURE 10 – PRE-CAST BENT CAP BEAM SUPPORTED ON SHAFT EXTENSIONS.

FIGURE 11 - PRE-CAST GIRDERS PLACED IN CAP BEAM OPENINGS.

FIGURE 12 - ALL PRE-CAST ELEMENTS PLACED IN DESIGNATED OPENINGS.

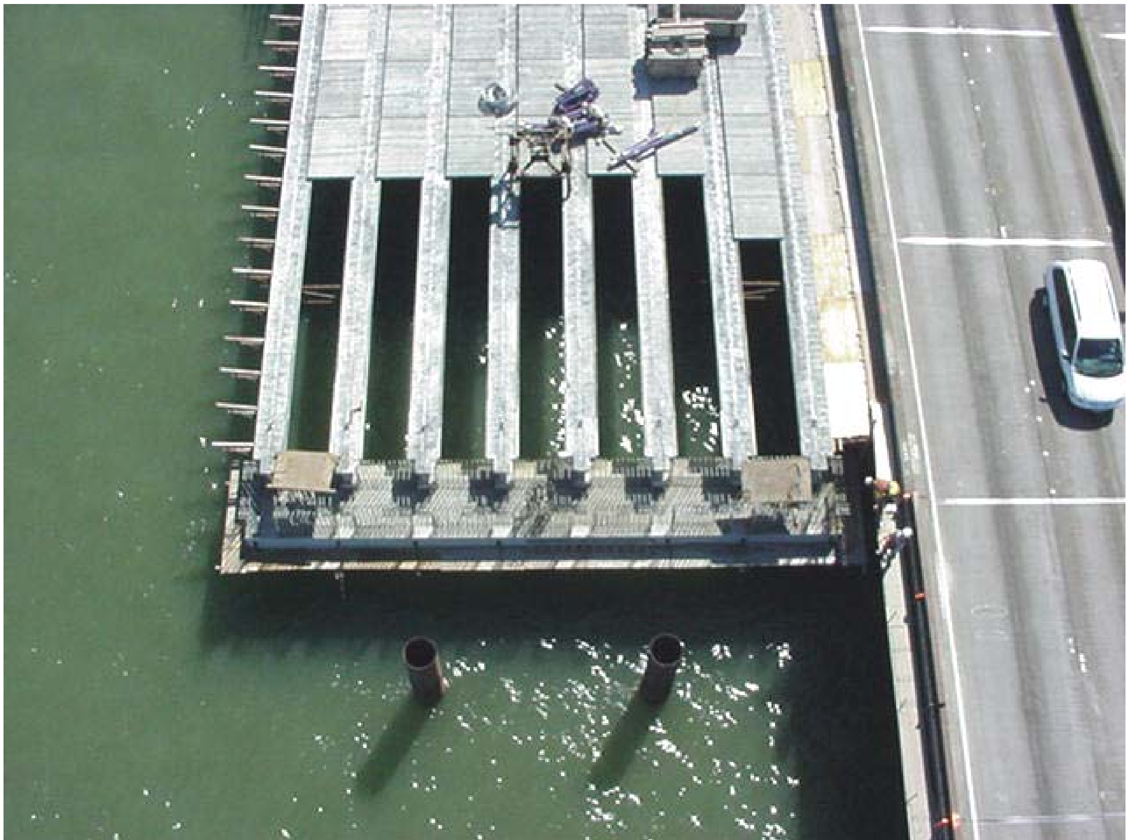

FIGURE 13 - TOP VIEW OF PRE-CAST BRIDGE COMPONENTS.

FIGURE 14 - CAST-IN-PLACE PORTION OF BENT CAP BEAM READY FOR CONCRETE POUR.

FIGURE 15 - MECHANICAL COUPLERS FOR MAIN GIRDER REINFORCEMENT.

FIGURE 16 - VIEW OF COMPLETED BENT CAP BEAM READY FOR TOP REINFORCEMENT.

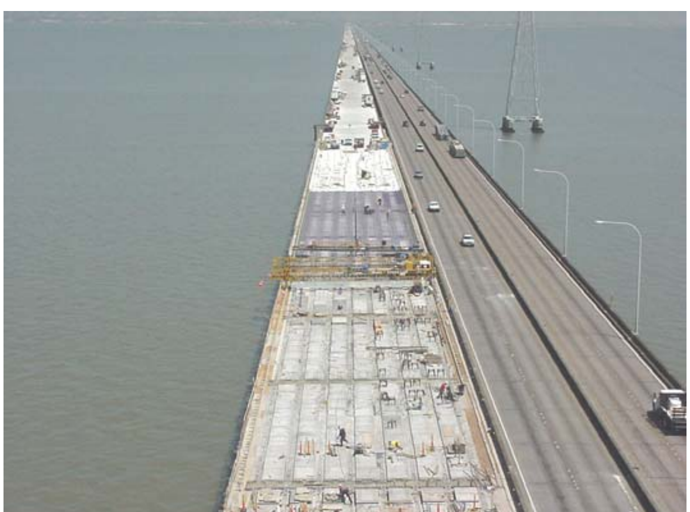

FIGURE 17 - SAN MATEO BRIDGE NEAR COMPLETION.

FIGURE 18 - SAN MATEO-HAYWARD BRIDGE OPENING CEREMONY.