SAN FRANCISCO-OAKLAND BAY BRIDGE
EYE BAR FRACTURE – LESSONS LEARNED

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Abstract

This paper provides an overview of the California Department of Transportation (Caltrans) response and lessons learned regarding the discovery of a fractured eye bar on the San Francisco-Oakland Bay Bridge (SFOBB) that occurred during the scheduled 2009 Labor Day weekend closure of the structure. In addition information is presented on the permanent repair design, forensic examination results of the failure of the eye bar and well as the temporary high strength rod that failed. Modifications to the SFOBB inspection plan are presented including the recently implemented remote monitoring system.

Introduction

The SFOBB opened in 1936 during the height of the Great Depression. For more than seventy years, this magnificent structure has carried millions of people safely and reliably between San Francisco and the East Bay. Today, the bridge serves more then 270,000 vehicles a day and is a critical link in the economy of the Bay Area, California, and the nation.

During a regularly scheduled inspection of the SFOBB, while the structure was closed over the 2009 Labor Day weekend, bridge inspectors found a fracture in one of the eye bars on the cantilever portion of the bridge that carries traffic between Yerba Buena Island and Oakland. The fractured eye bar is one of 1,680 eye bars on the eastern portion of the bridge, including 1,120 eye bars on the structure's cantilever section. Eye bars were a common construction technique used in the 1930s for truss members which are subject to only tension forces or for connecting bridge cables to their anchorages.

When the fractured eye bar was discovered, the bridge was already closed for the Yerba Buena Island Detour work as part of the new San Francisco-Oakland Bay Bridge currently under construction. As a precaution, the existing bridge remained closed until a repair could be put in place.

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FIGURE 1-THE FRACTURE PROPAGATED ACROSS THE FULL WIDTH OF ONE SIDE OF THE EYE SECTION OF THE EYE BAR.

When the fracture was discovered, Caltrans engineers decided to keep the bridge closed until the capacity of the eye bar was restored. With the bridge already closed to traffic, an emergency repair was initiated. A temporary repair strategy was developed incorporating the use of high-strength steel rods as part of a saddle apparatus to bypass the cracked area of the existing eye bar. That repair was installed and the bridge reopened on the day after Labor Day.

FIGURE 2-CLOSE-UP INSPECTION OF THE DIAGONAL EYE BAR WAS CONDUCTED.

Weekly inspections of the repair were initiated by Caltrans engineers to validate that all of the connections were tight and that the repair was performing as intended.

On Tuesday evening, October 27, 2009, a high-strength steel rod snapped from the steel saddle installed to repair the cracked eye bar. A portion of that assembly landed on the deck of the bridge. While there were no injuries, the bridge was immediately closed. Work began on a new repair and an investigation was launched to determine why the initial repair failed.

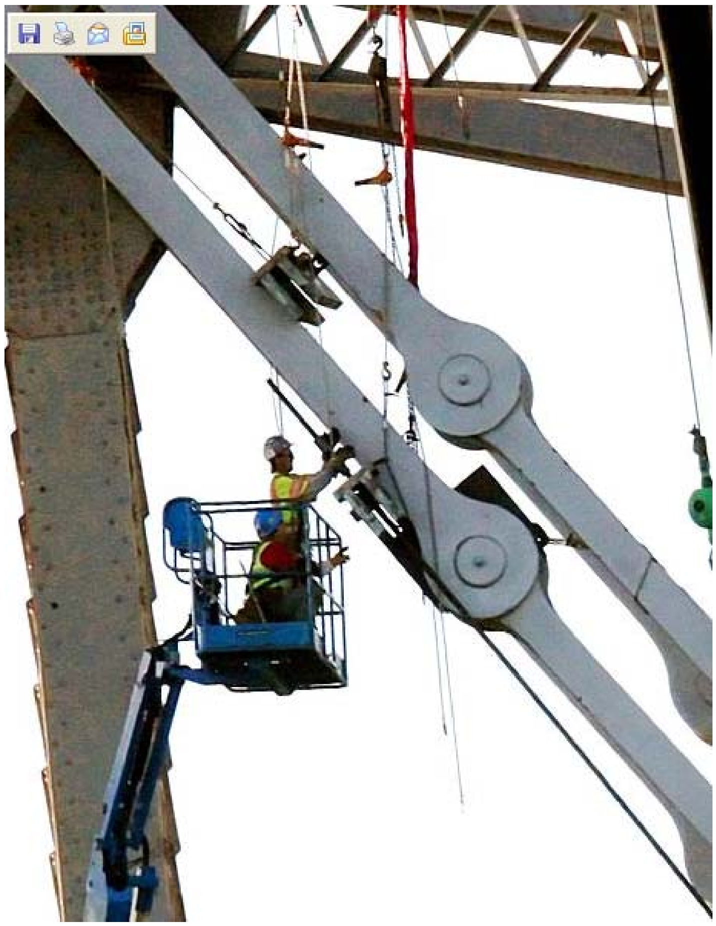

FIGURE 3-THE ORIGINAL FIX INVOLVED THE USE OF HIGH-STRENGTH RODS TO BYPASS THE CRACK.

Following the failure of the initial repair, Caltrans enlisted the assistance of outside experts to serve as a Peer Review Panel and assist in the development of a second short-term repair to allow for the reopening of the bridge: This repair included several design enhancements to the original short-term repair to ensure that the problem that occurred on the initial repair did not happen again. Tie rods were tensioned with a system that centered the rods through the holes in the saddle components to prevent metal-on-metal contact that could generate a stress concentration. The tie rods were strapped to one another and to the eye bars with a turnbuckle system to reduce vibration that could cause fatigue.

FIGURE 4-DAMPERS ARE DESIGNED TO REDUCE VIBRATION.

The crossbars attached to the tie rods were reinstalled to the saddles, essentially fusing them together as one piece. In the unlikely event of a tie rod failure in the future, the crossbar would remain attached to the saddle and keep the elements from falling. As a further precaution, the saddles were also chained to the pins and all repair system elements were tethered together to prevent them from falling onto the roadway.

The repair was completed and the bridge was reopened on November 2, 2009. With the bridge reopened to traffic, design work continued on a permanent repair to replace the capacity of the existing fractured eye bar.

Permanent Repair

The design of the permanent repair was to be more consistent with the original design of the bridge. Three concepts we initially considered: new internal eyebar, new eyebar head spliced to the existing body, and additional exterior eyebars mounted on pin extensions.

There were four design objectives to be met for the permanent repair: (1) restore eyebar to the original strength capacity; (2) minimize mass and stiffness changes; (3) restore pre-fractured tension to within 90% of original; and (4) provide a ten year design life.

The new internal eyebar concept was dismissed due to the need to unload and disassemble the entire eyebar chain. Two concepts were advanced into final design. External repair (supplement eyebars supported on pin extensions and internal repair (removing the fractured eyebar head and installing a structural steel hairpin over the pin and spicing it to the existing eye bar body.

The Internal repair was chosen because it best met the design objectives. A 12-foot section of the fractured eye bar was removed and replaced with new structural steel. Replacement of the eye bar head was done without the need for a full bridge closure by staff working at night with limited lane closures. The major work was completed just before the Christmas weekend, with some minor cleanup, and was finished early in January 2010. The Peer Review Panel reviewed and concurred with the long-term repair strategy.

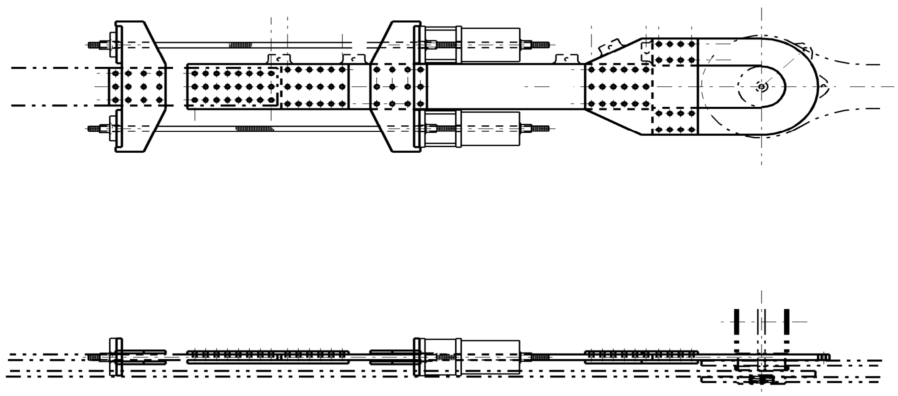

FIGURE 5-COMPLETED REPAIR OF THE PERMANENT EYE BAR.

Caltrans engineers visually inspected the permanent repair once a week for the first month after the repair was completed and are continuing to inspect it once every three months.

Forensic Examination

Following the initial discovery of the fractured eye bar, Caltrans launched both internal and external investigations to determine the cause of the fracture and potential implications to the long-term reliability of the structure until construction of the new eastern span of the SFOBB is completed.

A noted structure mechanics expert was hired to perform a forensic examination of the fractured eye bar. They were tasked with determining the following: where the fracture originated, possible causes, material properties and strength, and fracture toughness. While only steel from the cracked eye bar was subjected to detail testing, it should be noted that all the SFOBB eye bars similar to the one where the crack was discovered were designed to similar specifications and forged from similar material since the bridge opened in 1936.

This forensic information is important in assisting bridge inspectors as they conduct visual examination of eye bars on the SFOBB, the other three State highway bridges, and fifty-two local agency–owned bridges that also have this structural element.

A piece of the eye bar that contained the fracture was removed on November 7, 2009, by Caltrans personnel and delivered to the Laboratories for analysis. A second piece of the cracked eye bar was removed on November 13, 2009. These two pieces were used in the examination to determine the original material quality and any noted defects in the material as originally supplied for installation of the bridge, the crack initiation point, and the rate of crack growth.

Two reports concerning the eye bar were produced. In the first report, completed November 18, 2009, analysis concluded that a crack initiated at the outer edge of the eye bar and propagated toward the center pin location. The second report, dated February 9, 2010, validated the strength and toughness in the steel from which the eye bar was forged. The eye bars were manufactured using a die-press process that resulted in the eye bar heads having a concave side with sharp edges. Stress was concentrated in the sharp edges. The fatigue crack was initiated in this area of stress concentration.

FIGURE 6-DETAILED TESTS WERE PERFORMED ON THE STEEL FROM THE CRACKED EYE BAR.

A larger sample of the fractured eye bar was provided to complete the remaining tests. The sample was used to perform laboratory tests to determine the fracture toughness, as well as additional tensile tests, and fracture energy of the material. This information will be used to determine the requirements of the structural monitoring system to be installed on the bridge.

The Caltrans Office of Structural Materials also performed an investigation to determine the probable cause of the eye bar failure. (Copies of the reports are available on request).

It was concluded that after seventy years of cyclic loading, a fatigue crack initiated at the outside edge of the eye bar and propagated gradually to the center, leading to a loss of cross section. The loss of cross section exceeded the material's ability to carry the imposed load, leading to full cross-sectional failure.

FIGURE 7-CLOSE-UP OF FRACTURE SHOWING RADIAL RIDGES POINTING TO LOCATION OF CRACK INITIATION.

In addition, the cause of the failure of the high-strength rods used in the initial repair was investigated. The office's November 18, 2010, report concluded that the failure of the steel rod was caused by fatigue. Wind conditions on the bridge caused the rods to vibrate significantly, which was determined to be a contributing factor.

FIGURE 8-CLOSE-UP OF FRACTURE HS ROD.

Modeling/Analysis

An extensive computer analysis of the cantilever portion of the bridge confirmed that the elements of the bridge, including the eye bar chains, had load-carrying redundancy providing for an enhanced factor of safety.

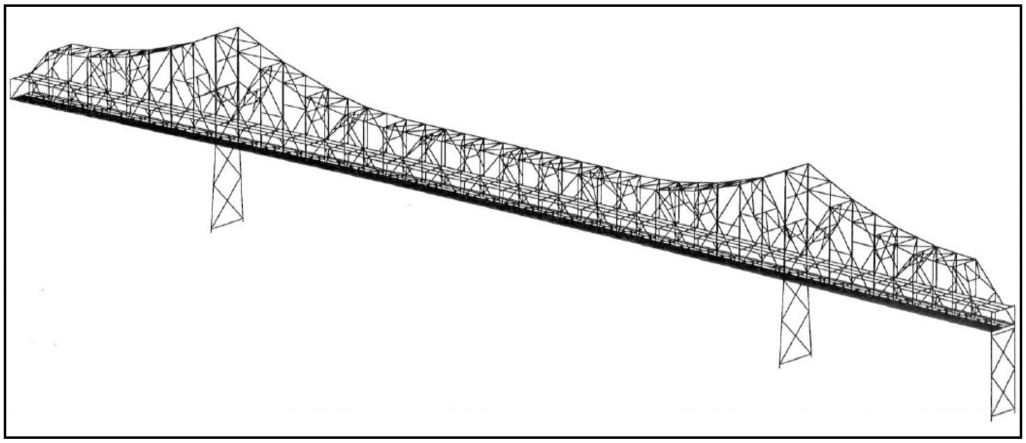

FIGURE 9-MODELING FRAME.

The design team had high confidence in the DL + LL from the original 1936 stress sheets and hand calculations. Caltrans also had analytical models of the SFOBB r from the seismic retrofit evaluations in the mid 1990's. The DL and LL were validated with these models. The design team had little information on re-distribution of loads to the adjacent members and uncertainty with the geometry prior to the fracture (pin rotation fracture width, etc…). The Sap model was modified to discretize the 8 eyebars into separate elements and parametric analyses were run to envelope the potential force level in the adjacent and adjoining eyebars. This instrumentation was instrumental in the design and jacking forces used during the temporary repairs and the permanent repair.

It was also this modeling and analysis that verified that the diagonal eyebar chains had the least amount of redundancy and ability to redistribute the load to other members if one of them failed. This is the basis of the Department focus of the inspection and monitoring on these sixteen diagonal chain locations on the bridge.

SFOBB (East) Inspection/Monitoring Plan

Nondestructive techniques are being used at the sixteen locations where eye bar chains are located. These inspection techniques include dye penetrant and ultrasonic testing. Dye penetrant testing involves spraying dye into the steel to identify surface imperfections. Ultrasonic testing uses sound waves to identify the presence of flaws in the interior of the structural steel. Areas of potential stress concentrations on the critical locations of the diagonal eye bars, such as concave surfaces and minor surface imperfections, have been mitigated by grinding the surfaces smooth. In addition, Caltrans structural steel technicians are performing dye penetrant testing and removing any potential areas where a crack could form on the exterior of the diagonal eye bars.

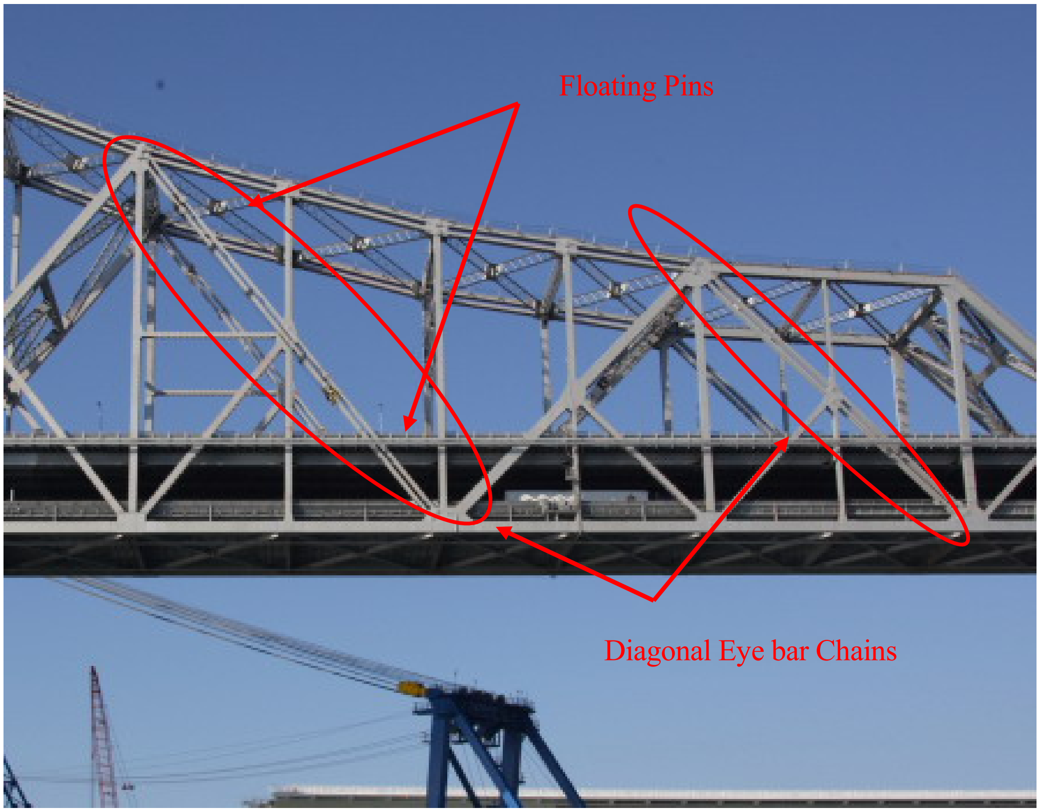

FIGURE 10-DIAGONAL EYE BAR CHAINS ARE CIRCLED.

Caltrans engineers are conducting visual inspections of the eye bars on the diagonal chains, including the one where the crack was found, every three months to identify any conditions that might require repair to ensure the safety and reliability of the bridge. The most recent inspection occurred in September 2010. No problems were found.

Vibration dampening systems have been installed at the sixteen locations with diagonal eye bars. Inspectors have observed a noticeable reduction in vibration of eye bars.

A contract was executed in July of 2010 to install a long-term structural health monitoring system on the bridge to Mistras Group, an international firm with its Northern California office in Benicia. The focus of this system will be the sixteen diagonal eye bar locations that are the most vulnerable to an eye bar fracture due to the configuration of the eye bar chain.

The proposed system will monitor sound on 384 eyebars for potential cracking frequencies 24 hours a day, seven days a week. The monitoring system consists of small sensors about the size of a quarter, epoxied to the eyebars and then wired to a central data collection point for transmission to an off site server. In the event that the steel cracking frequencies are "heard" by the system, Caltrans staff will be notified immediately by text messaging indicating the location of the observation so that visual confirmation can be made. The system will be installed by crews using lift truck in lane closures scheduled to minimize the impact on traffic.

Before the full installation, a demonstration will be carried out at U.C. Berkeley to verify that the proposed Mistras Corporation solution. The contract calls for full operation of system within 11 months from the award of the contract.

Conclusion

The fracture of an eye bar on the SFOBB was discovered during a regularly scheduled inspection and a repair was initiated. The technical examinations into the SFOBB eye bar failure confirmed that the crack on the eye bar was determined to have initiated on the exterior of the eye and propagated gradually toward the center. Caltrans has taken the following actions to ensure the safety and reliability of the SFOBB and other bridges with eye bars in California:

- Vibration dampening systems have been installed on the SFOBB at the sixteen locations with diagonal eye bars, resulting in a noticeable reduction in vibration of the eye bars observed.
- The SFOBB inspection plan was modified to inspect on a more frequent basis the critical diagonal eye bar elements similar to the one that failed, with inspections to occur every three months.
- The placement of a sophisticated monitoring system to alert bridge inspection personnel of any changes in the bridge's condition that could undermine the safety of the structure was initiated.
- Use of specialized structural steel technicians, trained in the use of dye penetrant and other nondestructive testing procedures, has been increased to detect any possible structural conditions that could require repair on all fifty-six eye bar bridges within California.

The Caltrans bridge inspection program is effective and Caltrans has taken the necessary steps to keep the SFOBB safe, continuing reliable traffic service for the remainder of its service life when the new Eastern SFOBB span is carrying traffic. The bridge will then be demolished.

The dedicated professionals at Caltrans are committed to ensuring the continued safety and reliability of the State and local bridges across California.