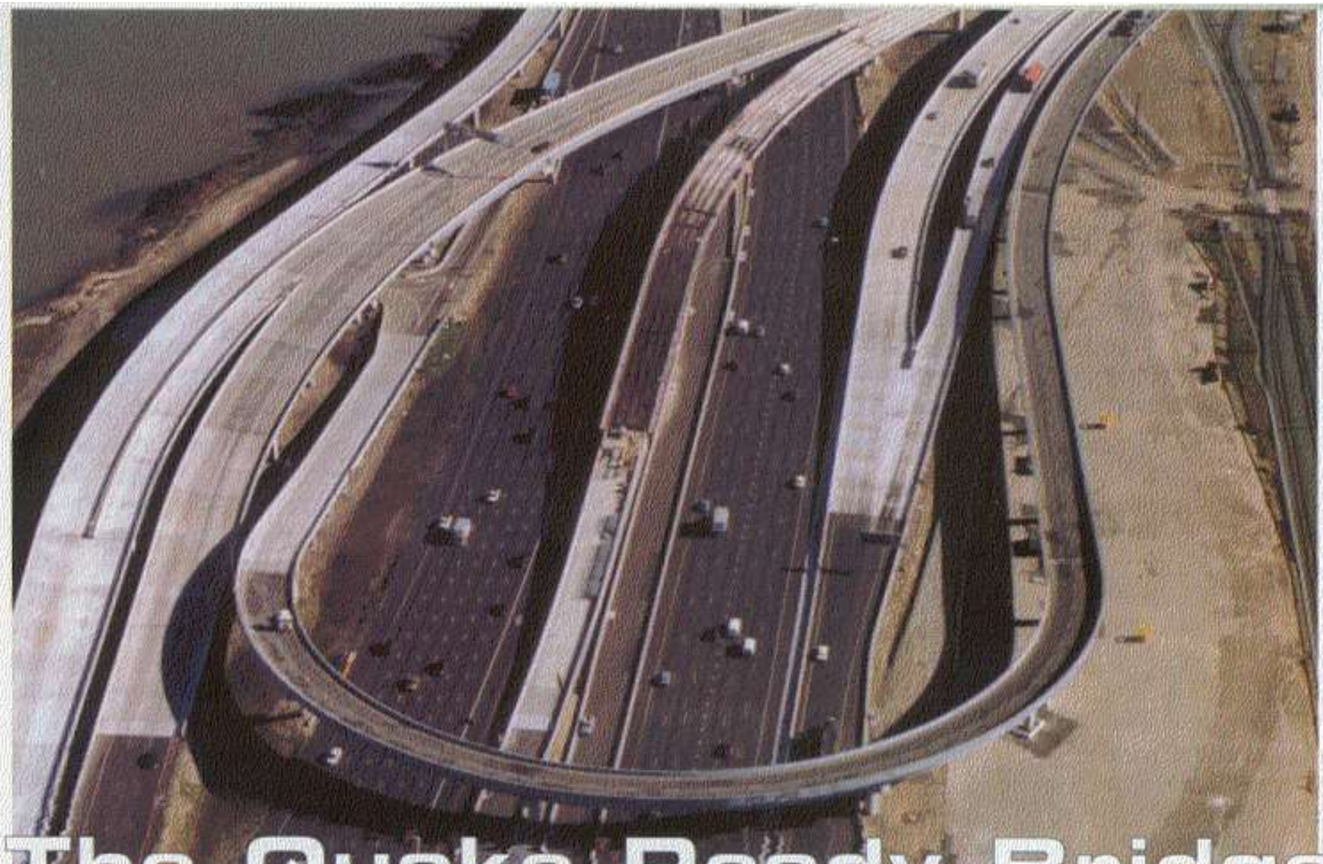

The Quake Ready Bridge

By James E. Roberts, Tony Marquez,
Carl Huang, Alfred Mangus,
John Williams, and Michel Benoit

It was October 17, 1989 when the Loma Prieta, a 7.1 magnitude earthquake, shook the cities of Oakland and San Francisco, Calif. The I-880 Cypress Street Viaduct, a two-level reinforced concrete structure completed in 1957, collapsed resulting in 41 deaths and 108 injuries. At the time, the I-880 freeway consisted of eight lanes, providing a daily flow of traffic, and carrying between 140,000 and 160,000 vehicles per day into and through downtown Oakland.

The replacement project was divided into seven construction contracts, A through G, and ranging close to $500 million dollars in bridgework. The I-880 Replacement Project bid for contract "E" was won by the general contracting joint venture of Kiewit/Marmolejo who was the successful low-bidder in the summer of 1994.

Contract E, worth $110 million, about 20 percent of all bridge work, is located at the intersection of Interstate I-880 and Interstate I-80. The $22 million bridge, with a length of 2,356-feet is known as the "Maritime Off-Ramp," and is a new and unique kind of curved steel orthotropic bridge that provides access to the Port of Oakland through a U-turn from Westbound I-80. The Horseshoe Line, or "HS" Line, is a 250-foot (76.2 meters) radius horseshoe shape, and is one of eleven bridges for Contract E.

On April 4, 1995 the steel plate was ordered and fabrication took place from June 6, 1995 through May 24, 1996. Kiewit/Marmolejo fabricated 13 full bridge width orthotropic sections 7'-0" (2.13 meters) deep by 35'-6" (10.6 meters) to 37'-6" (11.2 meters) wide, with lengths varying from 123 feet (37.4 meters) to 219 feet (66.7 meters) per section. Sections of the bridge ranged in weight from 250 tons to a maximum of 459 tons. All sections were shipped with a steel orthotropic deck and with the installed steel barrier rails. The total weight of all fabricated steel equaled 5,014 tons.

A 2,500-foot (762 meter) span suspension bridge currently under construction at Carquinez straits, and a proposed 1,400-foot (385 meter) span suspension bridge to replace the east cantilever truss span of the San Francisco/Oakland Bay Bridge, will become California's 9th & 10th orthotropic bridge.

Planning the New Bridge: Existing Steel Pipe Piles are Extracted for Corrosion Study

It was decided that three of the existing foundation piles would be exhumed to observe the possible amount of corrosion. After the 1989 earthquake, the I-880 Viaduct was demolished by California Department of Transportation (Caltrans), to the top of the footing elevation and covered up with backfill. A portion of the viaduct was not damaged and was saved for destructive testing of new seismic design methods.

Continues on page 30→

The new bridge foundations were designed to use steel pipe piles filled with concrete, similar to the old I-880 Viaduct foundation built in the 1950s. These new piles consist of a much larger diameter than the Caltrans standard pile details. New site borings revealed that corrosion protection should be considered, due to the presence of high levels of chloride, sulfates, and low values of minimum soil resistivities.

Ultimately, the intended goals of the three-pile exhumation were to examine the pile condition and rationalize an economical solution for corrosion protection of new bridges. Another goal was to view the seismic tension uplift test piles and compare them against calculations by bridge design engineers.

Caltrans decided that by drilling a series of holes at a full pile length alongside of a pile to be exhumed, these holes would then reduce the amount of skin friction. A vibratory hammer worked more effectively putting smaller forces on the pile and not overloading it. Eventually, the pile was completely removed, cut up into ten-foot segments, and then trucked to Caltrans' Translab in Sacramento for detailed inspection. Ultrasound thickness measurements were taken to determine how much metal was lost due to corrosion. Results of the corrosion testing can be seen in Figure 1.

Figure 1

Old I-880 Viaduct - Bent 91

- Tip elevation was at approximately at 46 feet. Shallow surface pitting corrosion, which occurred along the pile from one foot below the top of pile down 29 feet The maximum pit depth was 0.019 inches (19 mils) or about 1/64 of an inch.

Old I-880 Viaduct - Bent 75

- Tip elevation was at approximately at 55.5 feet (16.9 meters). There was no evidence of corrosion.

Old I-880 Viaduct - Bent 61

- Tip elevation was at approximately at 13.5 feet (4.1 meters). Minor surface pitting was found along the top five feet of the pile, generally above the level of the water table. Maximum pit depth was 0.016 inches (16 mils), about 1/64 of an inch.

Steel Pipe Pile Corrosion Protection for the I-880 Project

Most of the steel pipe piles used for this bridge were within 1,000 feet (304.8 meters) of salt water. Because of this pile, wall thickness was increased by a minimum of 0.250-inch over the structural requirement for the pipe. In addition, the piles located within 500 feet (152.4 meters) of salt water have been electrically connected for future monitoring and/or future cathodic protection. Assuming corrosion is constant, the additional thickness will resist corrosion for over 250 years. "HS" Line has 118,692 square feet (11,026 square meters) of 42-inch pipe piles and the total project had 3,335,326 square feet (309, 861 square meters) of other pipe piles.

By avoiding the use of corrosion inhibiting coatings, Caltrans Corrosion Technology Section was able to save between $6.7 to $13.4 million, approximately between $2 and $4 per square foot. With an additional sacrificial steel thickness of only 0.125", Caltrans expects the new piles life span to match or exceed that of the superstructure. The price of steel piling was approximately $0.33 per pound. Therefore, about $5.7 million were spent for additional steel wall thickness.

Another advantage of increasing wall thickness to combat corrosion is that the foundation system will be stronger than calculated. Paint and other coatings have no structural strength and may modify the soils to be coefficient of skin friction. Caltrans' policy is that the foundation system will be the most durable component of the structure and receive no damage in an earthquake. The reason for such a policy is that it is not practical to find pile damage easily or repair it.

Geotechnical tests took place and proved that the "soil set up factor" around piles was significant. Therefore, Caltrans with the Federal Highway Association (FHWA) funding, performed a comprehensive Indicator Pile Test Program from October 1993 to January 1994.

Indicator Pile Test Program for the I-880 Replacement Project

In order to gain a better understanding of the construction and design issues that are associated with the installation of large diameter steel pipe piles, an Indicator Pile Test Program was developed prior to the awarding of production contracts. Various pile installation methods were tested. Pipe piles were installed with both vibratory and impact hammers. The Indicator Pile Test Program reports were made available to all bidders for the I-880 Replacement Project. This eliminated major pile driving claims, resulting in a more competitive bidding process.

Foundation and Column Design

The hexagonal foundations with the seven, 42-inch diameter steel piles, were the result of a structural geotechnical and economical optimization study. The need for pile compliance at the interface of soft mud with the stiff underlayment lead to the use of steel piles. The deep overlying mud layer requires very long piles because of the high seismic loads that tend to exist. The hexagonal pile cap shape results from the "isotropic" nature of the seismic loading imparted by the soil structure interaction with the "plastic hinge" load reaction at the pier base. The bridge utilized reinforced concrete "T" bents with a single column with spiral reinforcing ties. Two special bearings connect the superstructure to each

"T" bent. New joint shear criteria for reinforced concrete design resulted in a higher level of reinforcement than previous projects.

Orthotropic Superstructure Deck Stiffness

The transverse flexural stiffness of the orthotropic steel deck is critical for the long-term behavior of the asphalt overlay. The weight-saving concerns, which guide the seismic design, dictate minimal overlay thickness. This leads to a compliant deck system, which is very sensitive to temperature and to local deflections imposed by concentrated wheel loads. The cyclic nature of this loading only increases the problem of compliance between overlay and steel underlayment.

Figure 2

- The identification of the main tributary factors such as local loads, dynamic amplifications, stress risers, residual welding stresses two-dimensional states of "hydrostatic tensile stresses," etc.
- The establishment of the relative importance and contribution of each of these tributary factors.
- The determination of the various strategies in design and fabrication to mitigate the most important "fracture-causing" elements.
- The recommendation of an optimal design and fabrication procedure, including choice of materials, quality control and inspection methodology.

The three primary factors affecting local failure and ensuing major damage and hence the life span of a structure undergoing fatigue loading can be seen in Figure 3.

Figure 3

- The tensile stress range amplitude.
- The flaw size within material welds which means quality of fabrication and inspection.
- The material toughness properties which means choice of specific steel.

The long-term delaminating danger of the overlay is greatly reduced by providing a uniform stiffening pattern with relatively closely spaced components and a relatively stiff top deck plate.

Fatigue

The overall stress range amplitudes under global loads are very low for this type of multi-cell box girders. The longitudinal continuity and the 180°± in plane "curve" further minimize longitudinal tensile stress ranges. The torsion stress components are very low for these large "cell perimeters". The resultant equivalent stress intensity values (Von Mieses yield criterion) are very low.

The local orthotropic deck stress ranges generated by localized dynamic wheel loading are more critical for fatigue, particularly at points of greater restraint and stiffness. These tend to occur at the intersection of deck plating and the longitudinal webs and the transverse diaphragms. Inclusion of the various stress risers and consideration of the weld types still hold to be excellent long-term fatigue capacities.

Fracture Control Plan

Maintaining the optimization of the safety and performance of the structure under minimal cost is the basic aim of a rational "Fracture Control Plan".

While buckling and general yield are considered in the basic design approach, special consideration is given to the danger of sub-critical crack growth and unstable crack extension. Special attention, at the design stage and subsequently at the fabrication stage, is given to the factors affecting these fatigue induced micro cracks.

The main elements of the fracture control plan can be noted in Figure 2.

The design philosophy is based on the concept of providing for "minimal" stress raisers through a careful choice of details and weld types. Redundancy is used with caution to minimize global and local stress range amplitudes and also to provide multiple load paths. Crack arresters are considered in various fracture-propagation scenarios. Web and flange local buckling are considered in a "limit load analysis" approach with given transverse imperfections. It is very essential to include actual fabrication conditions simulating imperfect geometry and welding residual stresses.

The web "slenderness" leads to some shear lag effect that needs to be considered in the local fatigue. This is also the case with the local buckling capacity of the most critical web panels at mid-span and near supports.

Unique Seismic Detailing Features

Currently, there are less than 50 orthotropic bridges in North America, eight in California alone. Asia claims over 100 bridges to be orthotropic, and Europe claims over 1,000. However, this bridge has several unique seismic detailing features including the use of rubber dock fenders as seismic shock absorbers reducing forces between completed bridge sections.

The rubber delta shaped "dock fenders" used, are designed to reduce kinetic energy occurring during a seismic event at the hinges of the superstructure. The systems were specifically developed for this bridge and are unique to Caltrans. Rubber fenders were used as bumpers to reduce forces transfixed in a compression shock wave in the longitudinal axis of the bridge. Larger delta-shaped rubber fenders were used as a part of a cable restrainer system. When seismic forces occur, there is a tendency to pull the bridge apart in segments at the two hinge sections. The lower masses

Continues on page 32→

At midnight welders preheat two spherical bearings. Preheating components is necessary to achieve a proper weld. Simultaneously, the orthotropic "section two" is being transported across west bound I-80 with the SHLHP equipment.

The side view of the orthotropic "section two" is carefully transported across westbound I-80 with the SHLHP equipment. Welders await to install the field splice plates with over 2000 bolts.

of the steel orthotropic superstructure, plus the energy damping system, reduce seismic forces on the concrete columns and substructure. PTFE (poly-tetra-fluoro-ethylene) spherical bearings have been used to allow rotation and expansion of the members. These bearings can resist higher lateral forces including seismic forces. Another feature within the project is the addition of a central shear key pipe for additional lateral capacity.

Midnight Construction

Due to given conditions, the project called out for a creative solution with the installation of the bridge. Bob Murphy, Heavy Haul Manager, quickly tackled the task by using a Special Heavy-Lift Hydraulic Platforms (SHLHP), (which consists of two self-propelled hydraulic platforms braced in tandem with a strut beam. A scale model was built to try out the various methods to preplan the most effective use of the SHLHP. On November 30, 1995, loading began from the manufacturing site on the north banks of the Columbia River adjacent to Portland, Oregon.

Closure of I-80 was required for setting three of the 13 sections. Approximately 500,000 vehicles cross below each day. The sections were staged on the East Side of the freeway and crossed over during night erection.

The first section was erected at the west abutment and allowed the team to practice for the erection over the freeway. The hydraulics of the SHLHP worked smoothly to position the section and lower it onto the steel bearings anchored to the top of the concrete pier. The section over I-80 westbound was erected about midnight Saturday, February 3, 1996. The section over eastbound I-80 was erected the following Saturday night. Once 25 percent of the bolts were installed plus the field welding of the section to the bearings, then the dead weight of the section was transferred to the splice and bearings. Finally the SHLHP was driven away. After the 13 sections were erected, the joint seal assemblies were installed and an epoxy asphalt overlay wearing was placed prior to opening the bridge to traffic.

Awards

MERIT AWARD

Design for Transportation National Awards 2000 — US Department of Transportation April 2000

SILVER AWARD

James F. Lincoln Arc Welding Foundation Awards Program — Lincoln Electric Company November 1999

GRADE SEPARATION AWARD

American Institute of Steel Construction — National Steel Bridge Alliance

Analysis

Various task-specific programs were used to simulate the static and dynamic behavior of the bridge structure Global Static Analysis. Dedicated pre- and post- processors allowed the designers to produce the governing load combinations for service and for ultimate conditions corresponding to the standard Load Factor Design (LFD). The approach was taken in accordance with the American Association of State Highway and Transportation Officials (AASHTO), the National Cooperative Highway Research Program (NCHRP), and Caltrans' Bridge Design Specification (CALTRANS-BDS) regulations. In addition, a special peer review committee created joint-shear design procedures for the reinforced concrete components.

Because of the seismic failure of the reinforced concrete Cypress Street Viaduct, Caltrans changed its methodology in designing reinforced concrete components. A much greater confinement is required around the reinforced concrete columns now. A detailed procedure was proposed by University of California at San Diego professors and adjudicated by a peer review committee of three distinguished engineers. If the design engineer found that the procedure resulted in an excessive number of rebars at a location, then this issue was discussed with the peer review committee. The reinforced concrete columns and footings were designed according to this "joint shear" procedure.

The designs of the orthotropic bridges were very specialized and Caltrans did not mandate that any specific calculation method be used. Kaiser engineers used proprietary finite element software "ABACUS" as well as in-house spread sheets to design the all steel superstructure. A literature search was also performed.

For more detailed information on Caltrans' actual calculation methodology please visit their Web site at www.dot.ca.gov for its design manuals.

Special attention was given to the expansion joints and to the foundations. Upper and lower bounds for the foundation's impedance were considered. The pier columns were also considered under two distinct states: elastic uncracked, assuming that no damage had occurred to the structure by the earthquake, and cracked, assuming that "no collapse" damage has occurred to the structure by the earthquake. The seismic analysis consists of the spectral response approach based on the Complete Quadratic Combination (CQC) modal superposition.

The Caltrans "no-collapse" policy means that the bridge has been damaged by the earthquake but continues to stand. Key bridges, vital to commerce, are designed to a higher level and are assumed to have traffic on the bridgeimmediately after an earthquake.

Caltrans' "Bridge Design Specifications," which is an amended version of AASHTO's Bridge Design Manual. The reason Caltrans has applied such stringent specifications for key bridges is because they must remain operational. Normally, bridges designed to withstand higher seismic force levels cost more to build. Therefore, it may be more cost effective and practical to seismically retrofit small secondary bridges that will not collapse after the earthquake. Since large earthquakes occur infrequently, Caltrans doesn't focus on making all its bridges indestructible to earthquakes, however it does aim at keeping the important bridges healthy and continuously operational.

Linear analyses were performed for a site specific "mud site" spectrum, corresponding to the maximum credible earthquake occurring on the Hayward Fault with an 8.0M magnitude, and alternatively, on the San Andreas Fault with an 8.5M magnitude. The seismic design philosophy is a displacement-ductility driven approach, which permits controlled plastic straining to occur at the various pier foundation bases. Soil-structure interaction analyses were performed by means of the finite-difference program. A trial and error iteration method was used to simulate the different material assumptions used to achieve meaningful sensitivity curves and to verify the compliant pile behavior for the very deep Bay Mud lay-

Continues on page 34→

Aerial view of the north half of the Cypress I-880 Replacement Project looking due west at San Francisco.

ers. Dedicated non-linear finite element models were developed for local web and diaphragm-buckling analyses for local wheel loading studies on the orthotropic deck.

Structural Design Features

No welds were allowed to cross over another weld and plates were coped to avoid the occurrence of a weld crossing a weld. The details were developed to reduce the number of locations where opposite face welding would occur since laminar tearing could result. The ribs were fabricated in tangent chords to accommodate the sharp radius of the superstructure. The ribs were welded as tangent chords to the top deck plate to approximate the radius of the girders. The specifications required this to be an 80 percent partial penetration groove weld. To ensure that welding would be of the highest quality, the specifications required that the rib welds be made using the automatic submerged arc process. Deck plates were oriented so that the grain or rolling direction of the steel plates was centered on the longitudinal axis of the bridge. Oval shaped personnel openings were provided throughout the interior of the structure for bridge maintenance inspections. Manhole openings and covers were added to the bottom palte of the superstructure.

The interior and exterior were painted with inorganic zinc rich primer for maximum corrosion protection. Drain openings were also added to the lowest point of the bottom flanges to allow drainage of water intrusion. Expanded polystyrene foam was installed in the ribs to prevent corrosion. By injecting polystyrene foam into the rib compartment, the coping was sealed in order to prevent entrance of moisture or other corrosion contaminants. This detail was also used on the Golden Gate Bridge.

The Golden Gate Bridge is maintained and owned by the Golden Gate Bridge Authority, a separate organization from Caltrans. In 1984 the redecking conversion from the original 1936 reinforced concrete deck was completed to the all-steel orthotropic bridge deck. Caltrans engineers provided technical support to the Golden Gate Bridge Authority.

An orthotropic steel barrier system using structural steel fabricated in the approved FHWA barrier configuration was designed. To reduce deadweight and simplify composite action welded steel was selected over the reinforced concrete rail system. The outside radius barrier was designed to be higher because of the heavy truck traffic using the sharp horseshoe bend over I-80 traffic. A portion of the barrier was fabricated in 20-foot-long (6-meter) components that bolt to an internal "W" flange system welded to the orthotropic superstructure. A series of access panels on the exterior allow the removal of a damaged barrier after a vehicle collision.

Why Orthotropic Bridges?

There are two seismic advantages of orthotropic bridges. The first is lower mass, the second is ductility. A heavier object receives greater force from an earthquake. Therefore, the higher the dead load of the superstructure, the greater the seismic forces received by the object. Ductility is the ability to withstand rapid changes between tension and compression during the shock waves. The 1994 Northridge Earthquake damaged welded steel frame buildings shocking the structural design community. This proves that steel structures give no absolute guarantee of seismic durability. Welding procedures and detailing are key to the success in resisting earthquake forces.

None of the eight existing orthotropic deck systems in California have been retrofitted. The only portions that have been seismically retrofitted were their concrete components.

The world's longest span bridges are in Japan and have orthotropic steel decks. They have built the longest suspension bridge (50 percent longer than any bridge in the world), the longest cable stayed bridge, and the world's longest floating bridge. They are using these designs due to the high amount of seismic activity that they are encountering every year in that region.

Caltrans' newest orthotropic bridges are being built to take advantage of the much lower mass of the orthotropic or all steel superstructure. Orthotropic can be cost effective for long-span bridges in non-seismic areas, since dead load mass will control the size of the components. The number one use of orthotropic decks across North America has been the redecking of older concrete deck suspension bridges to increase the life of the bridges.

The Future for Orthotropic Bridges

The future of orthotropic bridges is that in North America more and more will continue to be built. Engineers from around the world are building more orthotropic bridges because of the increase in use of personal computers. When German engineers developed construction formulas for bridges in the 1950's, they aimed at simplifying the complexity of the real structure. For example, steel deck plates are used in three ways. First, they serve as support for the wheels of a vehicle. Secondly, they serve as the top flange of the floor beam. And finally, the deck plates serve as the flanges of the main member of the superstructure.

- Steel piling corrosion did not occur after 35 years though some minor pitting did occur.
- Indicator Pile Test Program eliminated piling driving claims and established pile tip elevations for seismic loading.
- Largest pipe piling used was 42-inch diameter. 12-foot diameter pipe piles are planned for the Richmond-San Rafael project.
- Although the steel orthotropic steel bridge system is complex, it is a possible system to construct. An orthotropic superstructure is under a $189 million contract construction for the Carquinez Suspension Bridge to replace the 1924 Carquinez Cantilever Truss Bridge. This suspension bridge is the first in U.S. history in 30 years. The orthotropic superstructure is currently under final design and testing by the San Francisco Oakland Bay Bridge design team.

Today's engineers have the capacity and capability of accessing and using sophisticated "finite element" programs on their personal computers. These programs are allowing engineers to develop and plan designs much more accurately. Existing orthotropic bridges have been standing for over 30 years. This has given the opportunity for engineers to understand the performance of wearing surfaces and actual rates of fatigue cracking.

Northern California's orthotropic bridges, the Golden Gate Bridge, Hayward/San Mateo and Miller-Sweeney Bascule Bridge, survived the 1989 Loma Prieta earthquake undamaged.Southern California's orthotropic bridges survived undamaged from the 1994 North Ridge Earthquake.

These bridges remained operational immediately after the quake. All three needed some form of a seismic retrofit, but the orthotropic superstructure remained unchanged. Research professors around the world have been studying fatigue issues that pertain specifically to orthotropic bridges. Recent work at the University of Lehigh has produced a next generation of orthotropic bridge decks.

The future for orthotropic bridges are immense in North America, and are in the plans for many engineers because of the reasons mentioned above.

Photography by Bob Colin. Aerial photos by Lynn G. Harrison of Caltrans

Owner: Caltrans (California Department of Transportation), Sacramento, CA
Engineer: ICF Kaiser Engineers, Inc. and Construction Group, Oakland, CA
Fabricator: Universal Structural, Inc., Vancouver, WA
Erector: Shaughnessy and Company, Auburn, WA
Lifting Specialist: Crowley Maritime Services, Inc.
Detailer: Candraft Detailing, Inc., Port Coquitlam, and British Columbia
General Contractor: Kiewit-Marmolejo (A Joint Venture)
Structural Steel Plate: Bethlehem Steel Corporation, Burns Harbor Division, IN

Official Name: Maritime Off-Ramp
Nickname: "HS" Line or "Horseshoe-Line"
Width: 36.2 feet
Length: 2356 feet
Deck Area: 85,287 square feet
1994 Bid Price: 22.3 million
Pounds of Steel: 10 million
Cost of steel per pound: $1.34
Lbs. of steel / sf of deck: 117 psf
Bridge cost per square foot: $262
Notes: Steel cost was 60 percent of the total
CALTRANS Bridge Number: 33-6235