DESIGN AND INSTRUMENTATION OF THE NEW SAN FRANCISCO-OAKLAND BAY BRIDGE EAST SPAN

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Abstract

The new east span of the San Francisco-Oakland Bay Bridge is under construction now. It is the most expensive public works project in California's history. The bridge is designed to provide a high level of seismic performance. Even after a major earthquake, the bridge is intended to provide full service almost immediately and should sustain only repairable damage to structure. During the construction, a total of 199 strong-motion sensors will be installed at key structural members along the bridge. This paper presents various structural systems used along the bridge and discusses the instrumentation plans.

Introduction

The San Francisco-Oakland Bay Bridge (SFOBB) is an integral part of the region's transportation. This structure links two of the largest cities in northern California and is vital to the economy of the area. The east span of the SFOBB, a double-deck truss bridge built in 1937, was damaged during the 1989 Loma Preita earthquake. It was determined that a complete seismic retrofit of the current bridge was too costly for the aging structure and that the funding was better suited being used for a new crossing. Figure 1 shows a rendering of the bridge.

The construction of the new east span was broken up into four major structures:

1. The Yerba Buena Island Transition Structure,
2. The Self Supporting Suspension Structure,
3. The Skyway Structure, and
4. The Oakland Touchdown Structure.

The Skyway project was the first to get started and consists of single column support bents with a concrete box superstructure. The foundation has large diameter cast in steel shell (CISS) piles battered away from the center of the pile cap. There are two separate structures, one for eastbound and the other for westbound traffic. The Yerba Buena Island (YBI) Transition Structure is designed to bring the two side-by-side roadways from the self-supporting suspension structure and stack them on top of each other to utilize the existing double deck tunnel cored through the rock of the island. The transition structure also has a single column concrete box girder configuration.

The Self-Supporting Suspension Bridge has the support pier off set from the center and is referred to as the “Signature Structure”. The suspension cable is wrapped around the ends of the bridge and relieves some of the downward loads at the supporting piers. The Oakland touchdown consists of a thin concrete box girder superstructure on a single support pier. The concrete pier is supported on a concrete pile cap with nine piles. The touchdown structure ties into a landfill area that leads to the toll plaza.

Figure 1. A rendering of the new San Francisco-Oakland Bay Bridge East Span.

A total of 199 strong-motion sensors are planned to be installed on the SFOBB East Span. They consist of force-balance accelerometers, relative displacement sensors and tilt meters. The locations of these sensors are shown in Figure 2. The sensors are connected via cables with the recorders centrally located at several places on the bridge. The analog signal from each sensor is converted to digital data and stored in the recorders. The relative displacement sensor provides direct measurement of the relative displacements between two points on the structure. The acceleration data are routinely processed and integrated to obtain velocity and displacement (absolute) records. All the recorders have clocks and are connected to have a common triggering, so the recorded response data will be synchronized. The instrumentation includes free-field and downhole sensors at both ends of the bridge.

Since more than half of the mass is on the foundation and the soil-structural-foundation interaction is complicated to model, a lot of sensors are needed to measure the input motions and the foundation response. When the locations of the sensors were planned, one major objective was to install as many sensors as possible on the pile caps and the pile tips. These sensors would record differential ground motion along the bridge and capture the traveling seismic waves as they are propagated from one end of the bridge to the other. Although the installation and maintenance of these sensors are more expensive, installations of some of these locations would be impossible after the construction is complete.

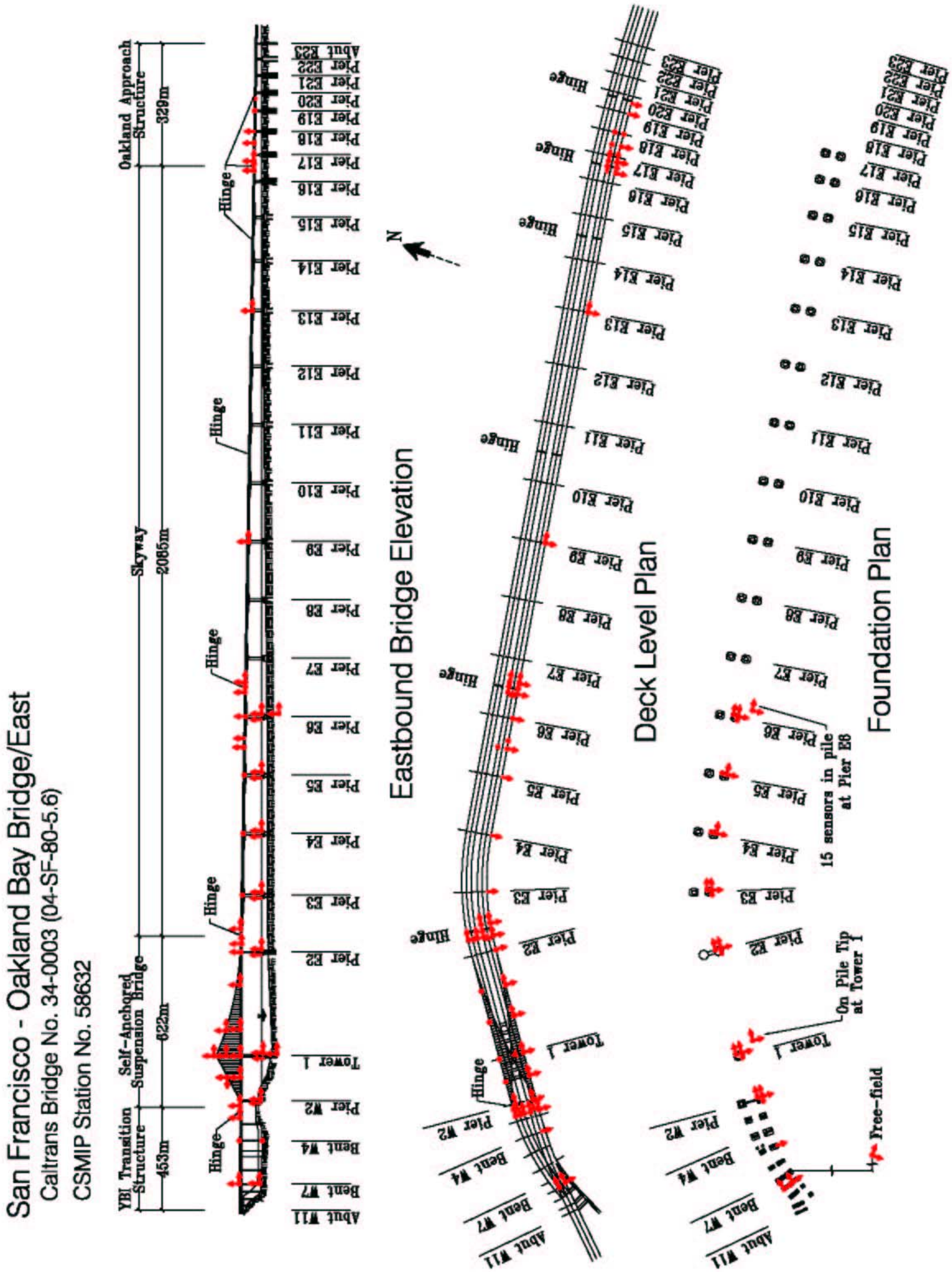

Figure 2. Locations of strong-motion sensors to be installed on the SFOBB East Span.

Self-Anchored Suspension Bridge

The self-anchored suspension bridge consists of a 385 m main span and a 180 m back span (Figure 3). The 160 m tall single tower consists of four steel shafts connected with intermittent steel shear links along its height (Figure 4). Each shaft is tapered and made of stiffened steel skin plates. The tower is supported on steel pipe piles driven about 100 meters into Francisco rock. The east pier is supported on steel pipe piles founded on the Alameda Formation and the west pier is supported on a massive 12.5 m deep footing supported by piles.

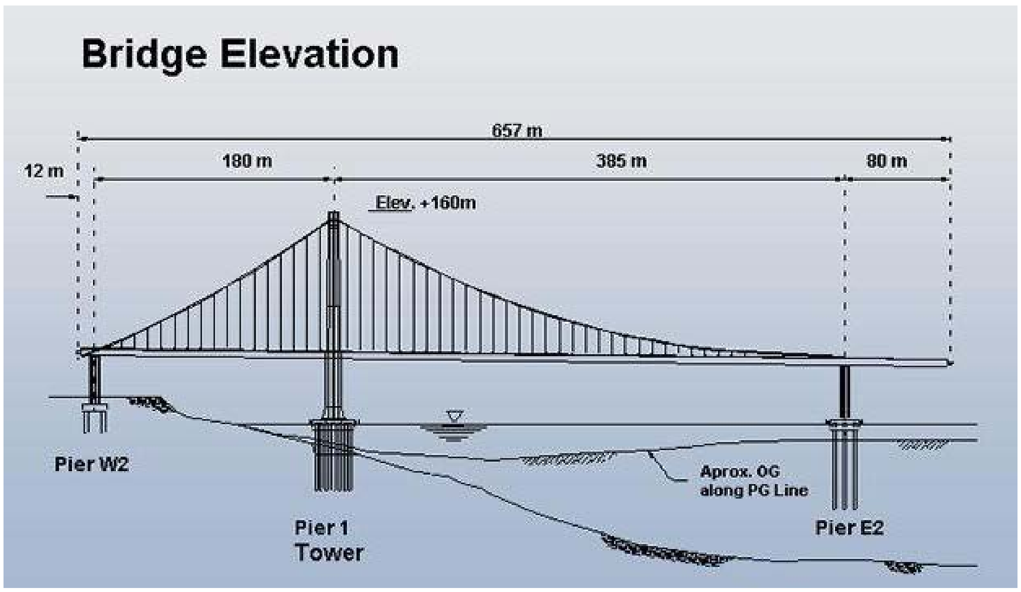

Figure 3. Elevation of the SFOBB Self-Anchored Suspension Bridge.

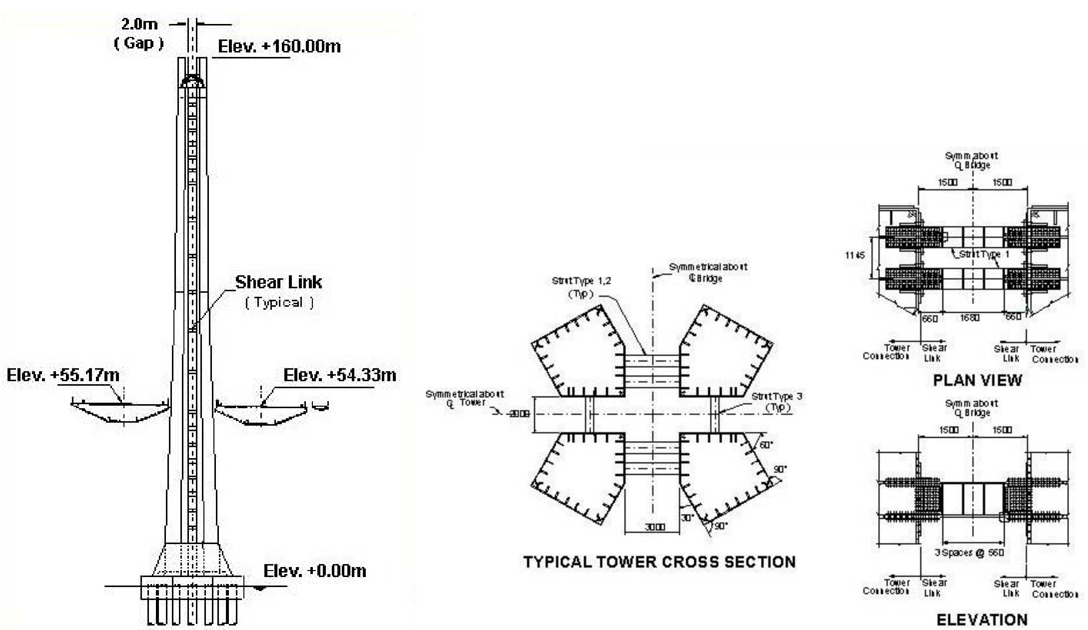

Figure 4. Elevation and Section of the Single Tower for the SFOBB Self-Anchored Suspension Bridge.

The tower shafts are designed to remain elastic under the design level earthquake while the shear links are permitted to yield in shear providing energy dissipation. The links can be removed and replaced without closing the bridge. The suspended bridge deck consists of dual, hollow orthotropic steel boxes. Each box girder has a 25 m wide deck carrying five lanes of traffic in each direction (Figure 5). In addition, a 4.8 m wide pedestrian/bike path is provided on the eastbound structure. The box girders are connected together by 10 x 5.5 m crossbeams spaced 30 m apart (Figure 6).

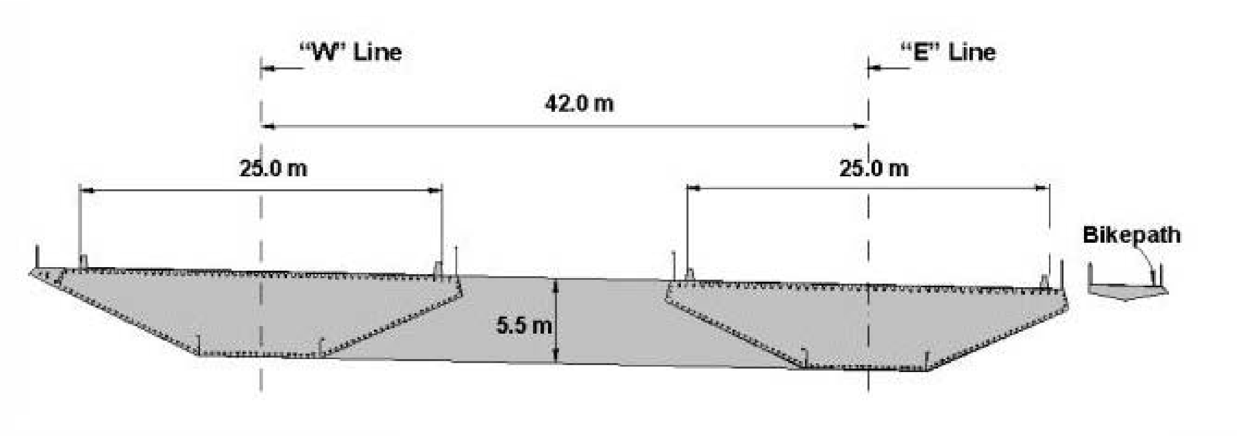

Figure 5. Cross section of the steel box girders at the SFOBB Self-Anchored Suspension Bridge

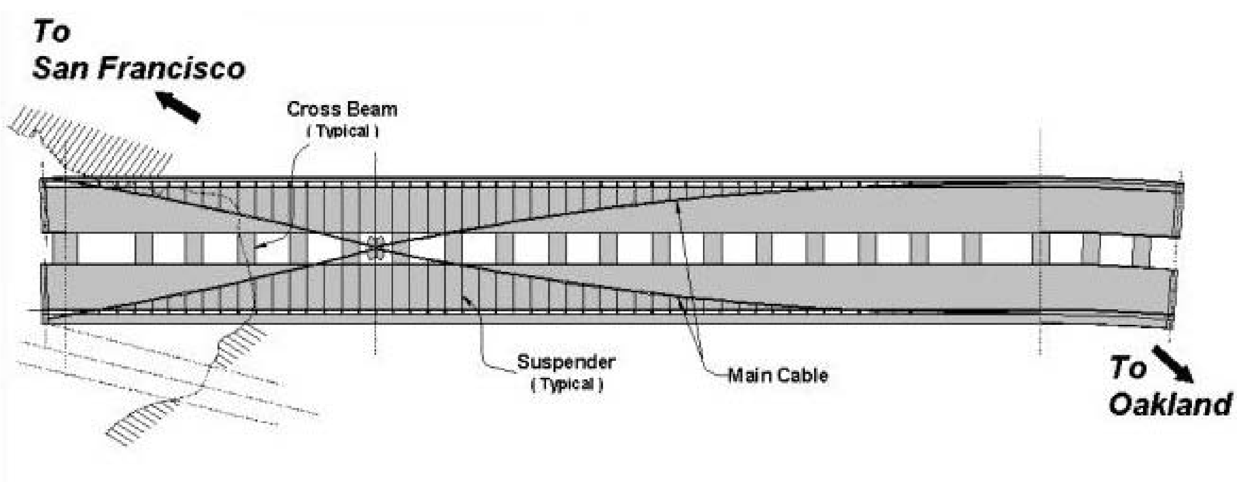

Figure 6. Plan view of the SFOBB Self-Anchored Suspension Bridge with steel box girders, cross beams and suspension cables.

The east piers are concrete columns supported on 16 steel shell pipe piles. These piles are 2.5 m in diameter and 100 m long. They are filled with earth up to 55 m from the top and the rest is filled with concrete. The box girders are supported on bearings at the east piers. Shear keys and tie rods are provided to carry lateral loads and uplifts, respectively. The west piers are concrete columns enclosed by a steel shell. At the west pier, a tie-down system with 28 stay cables is designed to resist possible seismic uplift. The cables are anchored into the footing. The box girders are supported at the east and the west pier for lateral loads and are "floating" at the tower.

The design of the Self-Anchored Suspension Bridge was based on the results of time history analyses that include multiple support excitation, nonlinear geometry and nonlinear material properties. From the computer models, the periods of vibration are 4.5 (dominated by vertical motions), 3.8 (longitudinal motions), and 3.6 seconds (lateral or transverse motions) for the first three modes. The mode shapes are shown in Figures 7 and 8.

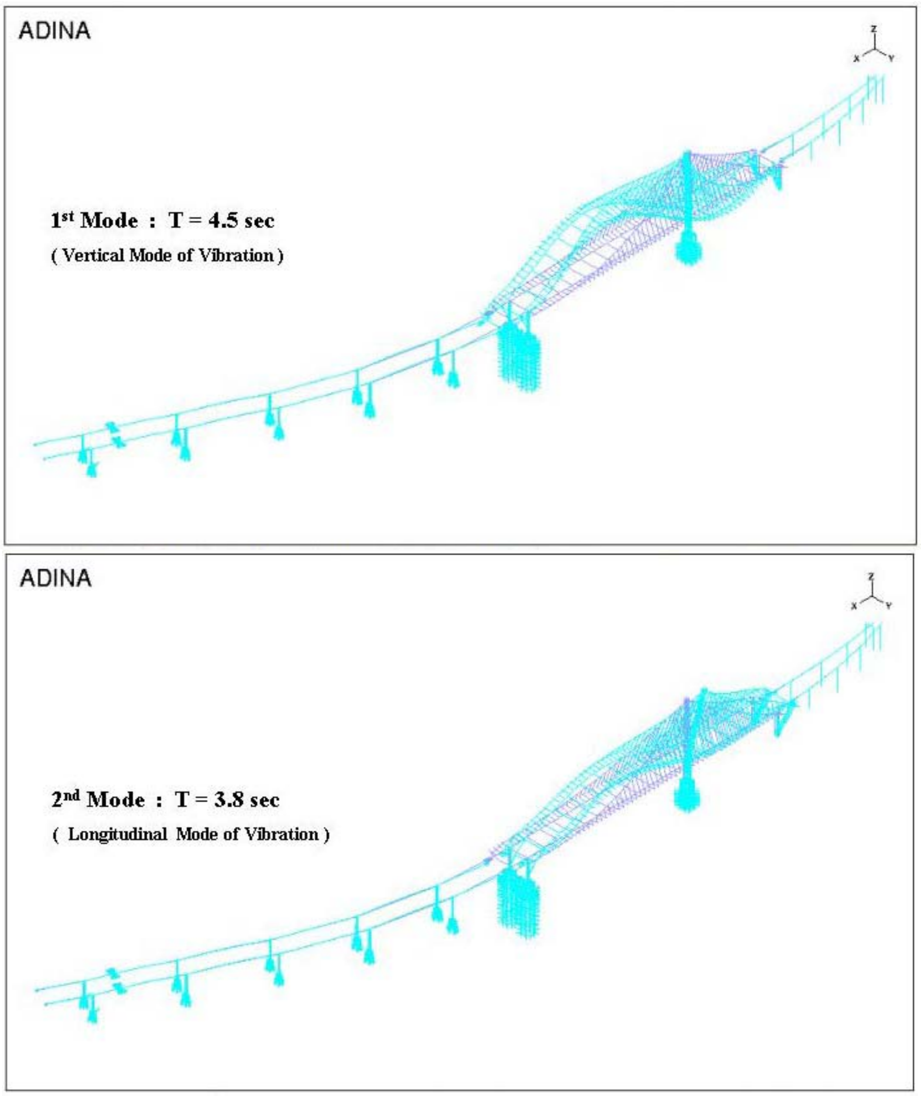

Figure 7. Modal periods and shapes for the first two modes of the SFOBB Self-Anchored Suspension Bridge.

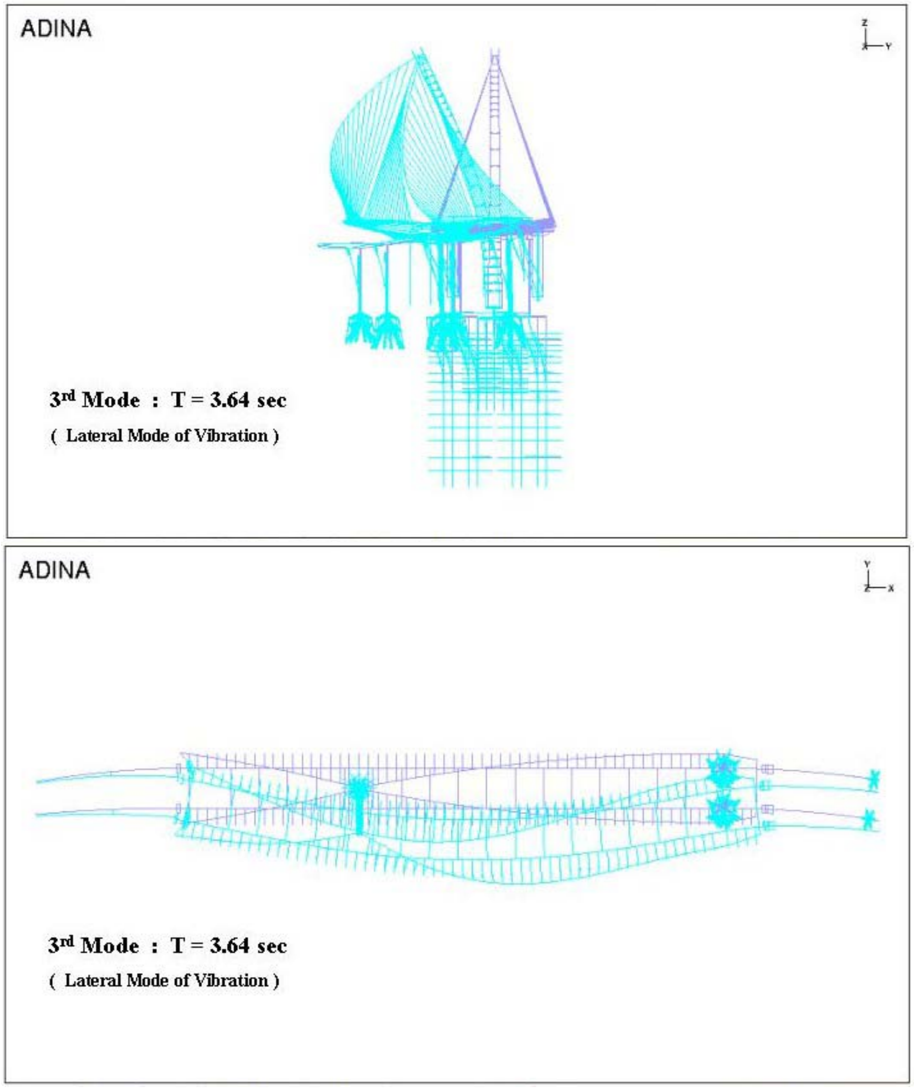

Figure 8. Period and mode shape for the third mode of the SFOBB Self-Anchored Suspension Bridge.

The seismic displacement demands at the tower, and the east and west piers are shown in Figure 9. On each end of the suspension bridge, the transition to YBI structure and the Skyway structure, the hinges are designed to allow the structures to move relative to each other in the longitudinal direction, but key the structures together in the transverse and vertical direction (Figure 10). At the each hinge, two 60-feet-long steel pipes (6 feet in diameter) are placed inside stainless steel sleeves. The pipes are designed to fuse during a major event and can be repaired.

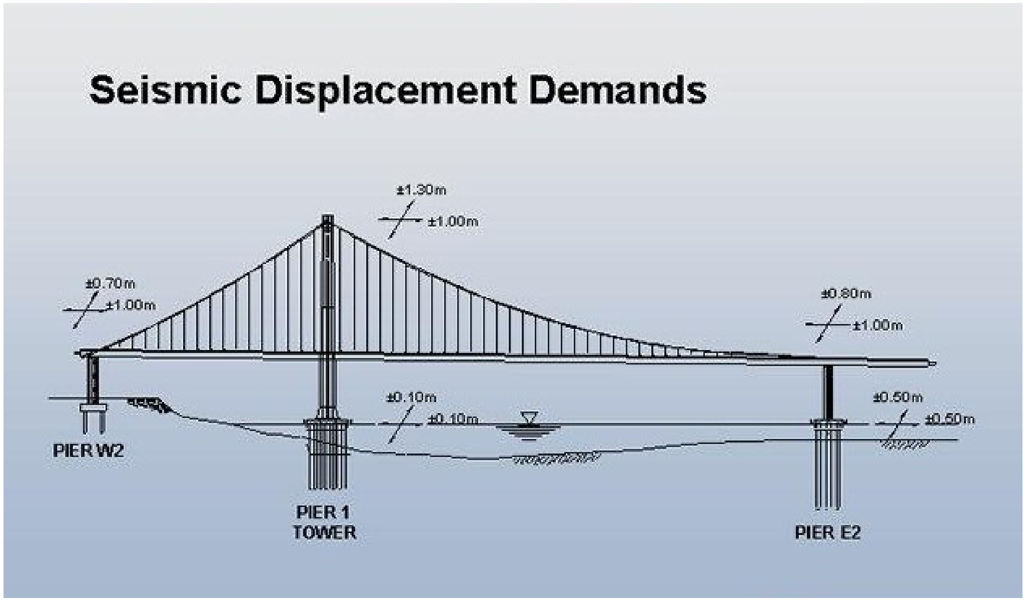

Figure 9. Seismic displacement demands of the SFOBB self-anchored suspension bridge.

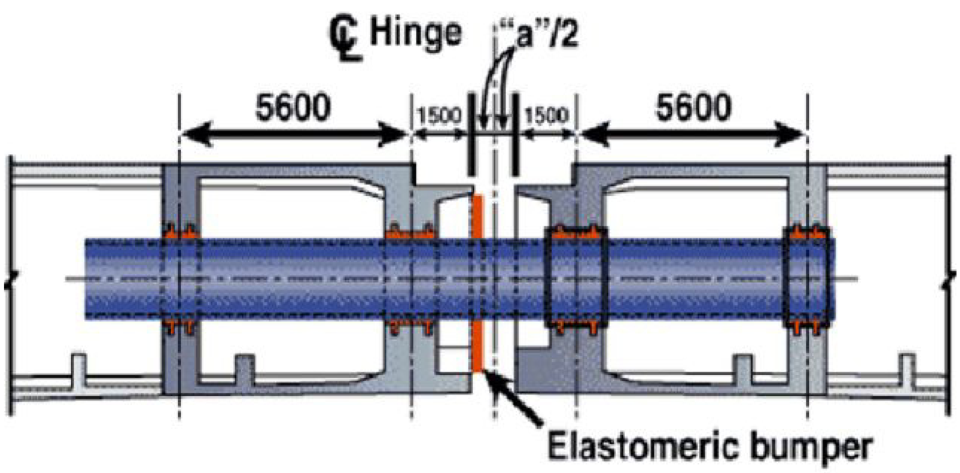

Figure 10. Hinges on both ends of the SFOBB self-anchored suspension bridge.

During the planning for strong-motion instrumentation, it was decided that a large number of the sensors (86) should be placed on the Suspension Bridge since it represents the most unique design and accrues much of the cost. First, the entire structure was looked at in the global sense and sensors were placed at intervals along the entire structure to capture the overall response.

The boundary conditions at the hinges will be monitored well with accelerometers and relative displacement sensors to help understand the bridge integrity and seismic response interactions among different structures. Each of the three pile caps for the suspension bridge will have six sensors to measure three translational as well as three rotational components of the motion. The main tower will have sensors at the base, road level, mid-height and at the top to measure motions of this critical supporting structure. The cables and the roadway will also be monitored along their entire length to measure their responses to ground shaking. A tri-axial "downhole" sensor will be placed near the tip of one of the tower piles to measure the input motion from the rock. Some sensors along the deck are placed opposite each other in the vertical direction to indicate if the deck structure is twisting or moving in phase, along the length of the roadway.

The self-anchored suspension bridge has its cables crossing over the tower and then wrapped around each end to partially relieve the vertical loads at the piers. This is another reason why the hinges are monitored well to record the motions of the ends of this unique signature structure. Since the tower is not centered in the structure, unusual torquing motions can be expected in a large earthquake.

YBI Transition Structures

The eastbound and westbound transition structures connect the suspension bridge to the existing double-deck tunnel at the Yerba Buena island. The two structures are carried on separate single-column bents, except near the viaduct end where they are supported on outrigger bents. The length of each transition structure is approximately 467 meters.

The YBI Transition Structure is lightly instrumented due to its more common construction and funding issues. One outrigger (Bent W7) is instrumented fairly well in all directions at the base of the columns and at the beam level. Outrigger bents on other bridges have experienced damage in the past and much is to be learned by studying their motion. This outrigger bent also has one column that is shorter than the other column, and the load distributions will be different during vibrations. A "free-field" sensor, which will record the bay shore movement, will be placed near Bent W7.

The next area of study at the YBI Transition Structures is where the structures meet the Signature Structure. The second bent from the hinge will have sensors at the base and top of the column to observe the relative displacement of this column (Bent W4R). The transverse motion sensors, from Bent W4R past Bent W3R to the hinge, will record the mode shapes of this segment of the structure. The hinge between the transition structure and the suspension bridge is instrumented well. A displacement sensor will be placed longitudinally at the hinge to measure directly the opening and closing of the hinge over time and will reveal if there is any change after an event. A total of 28 sensors will be placed on the YBI Trasition Structure.

Skyway Structure

The Skyway Structure represents the longest segment of the crossing and was the first to start construction. The Skyway is a 2.4 kilometers long pre-cast segmental concrete viaduct with varying span lengths from 120 to 160 meters. The 160 meter spans are arranged in frame units of three or four piers per frame with a girder depth of 5.5 m at the mid-span and 9 m at the pier. There are four frame structures for the skyway. The hinges between the frames allow longitudinal expansion and contraction caused by creep, shrinkage, and temperature changes. An internal steel beam assembly at the hinge provides shear transfer and moment resistance in addition to controlling deflections at the cantilever end of each frame. These beams are rigidly connected to the box girder at one end and slide on bearings at the box girder on the end.

The Skyway structure will have 452 separate roadway segments, most of them 25 feet long. Each segment consists of a 3-cell concrete box girder that is 90 feet wide. These segments are pre-cast at a pre-cast yard and then transported to the bridge. The bridge superstructure is supported on cast-in-place columns with four confined corner elements interconnected by shear walls. The foundation system consists of a 6 m deep pile cap supported on large diameter battered steel piles filled with concrete. The foundation is designed to be stiff to limit the elastic displacements of the pile caps to acceptable levels and minimize the potential for permanent offsets during earthquakes.

The instrumentation of the Skyway structure will focus on the first frame structure that is adjacent to the suspension bridge. The remaining three frame structures will be instrumented with 3 to 8 sensors. The hinges between the suspension bridge, the Oakland approach, and the Skyway. will be monitored well. The hinge between the first and second frames will also be instrumented. At the first frame structure, many sensors will be placed to capture the longitudinal and transverse deck level mode shapes concentrating the efforts at the deep-water piers. The pile caps of the four piers for the first frame structure will have 4 to 6 sensors placed on them to record the pile cap motions. In addition, at Pier E6 an intense array of tri-axial downhole sensors will be added to one pile at five various elevations to record the full height motions of this pile. It is hoped in the future to build a pier near by this instrumented pile to record the bay mud motions at the same elevations as the pile instruments for comparison of the soil motions to the pile motions.

Three relative displacement sensors will be installed at the hinges at the beginning and end of the eastbound bridge and at one intermediate hinge. Near Pier E6, vertical sensors on each side of the deck will be located in the span to record the vertical and torsional response of the superstructure. A total of 73 sensors will be installed on the Skyway Structures.

Oakland Approach Structures

The westbound approach structure is about 660 meters long and includes an elevated section and a section that is essentially on grade. The eastbound approach structure is an elevated frame structure and is about 329 meters long. The elevated structure consists of a cast-in-place concrete box girder supported on concrete piers, concrete footings, or concrete piles.

The Oakland Approach Structures will be lightly instrumented but a downhole geotechnical array is planned to be installed near the approach structure. The eastbound approach structure will be instrumented with 12 sensors that will record the motions at the transition between the Skyway and the Approach, and the lateral and torsional motions of the deck.

The geotechnical array will use four tri-axial subsurface sensors at various depths and one surface instrument (15 sensors total). The planned depths are surface, 50, 150, and 300 feet, and 520 feet down into rock. This will measure the motion from the bedrock up through various soil conditions to the ground surface. The data can be used to calibrate site response model used in geotechnical earthquake engineering. The deepest hole will be logged by a geologist to determine the subsurface conditions at the site and will be P/S suspension logged to determine the seismic wave speeds for the full length of the hole.

Summary

The San Francisco-Oakland Bay Bridge is a multi-billion dollar project and represents a huge investment for the people of California. The 3.5 kilometer long structure needs to be monitored for strong seismic movement. The strong-motion data can be used not only by bridge engineers to calibrate and improve their computer analysis models but also for Caltrans to rapidly assess the structural integrity after a major event. A total of 199 sensors are planned to be installed along this structure at key structural elements to achieve the measurement objectives and to capture important modes of bridge vibrations. After the strong motion instrumentation systems are in place they will also need to be properly maintained to successfully record future earthquakes. Even smaller quakes can yield useful data for engineers to understand the seismic response of the bridge. Ultimately, the recording of a major event will advance the field of earthquake engineering.