
The reinforcing steel for each pier is designed to help the structure withstand a major seismic event. A circular well-confined column is located at each corner of the pier.

BUILT TO RESIST THE BIG ONE

by Daniel C. Brown

This is a bridge for the record books. Now nearly complete, the San Francisco-Oakland Bay Bridge Skyway is a world–class concrete structure for several reasons:

- Its precast girder segments are some of the largest bridge segments ever built in the world. The huge segments weigh 300 to 800 tons, whereas more typical segments weigh 40 to 60 tons.
- The structure's pre-tied reinforcement cages are among the largest ever set in North America. The pier column reinforcement cages, placed in one section, weigh up to 300 tons.
- The bridge has its foundations in deep Bay mud, yet it is close to two major California fault lines and must resist a major earthquake.

profile **SAN FRANCISCO-OAKLAND BAY BRIDGE — SKYWAY SECTION** / OAKLAND, CALIFORNIA

ENGINEER T.Y. Lin International/Moffatt & Nichols, a joint venture

PRIME CONTRACTOR Kiewit/Flatiron/Manson, a joint venture

CONCRETE SUPPLIERS Pacific Cement, San Francisco (precast); RMC Lone Star, Davenport, Calif. (ready mixed)

PRECASTER Kiewit/Flatiron/Manson, a joint venture

CONSTRUCTION ENGINEER Parsons Transportation Group, Oakland, Calif.

POST-TENSIONING AND SEGMENT ERECTION EQUIPMENT Schwager Davis, Inc., San Jose, Calif.

Kiewit/Flatiron/Manson set up a precasting yard in Stockton, Calif., and barged segments to the job site. This long-line casting bed can cast all the segments needed for one cantilever.

Untold hours went into the seismic design for this $1-billion precast concrete segmental bridge, resulting in a unique bridge that extends the limits of concrete design

The San Francisco—Oakland Bay Bridge consists of 16 separate contracts, and the Skyway, which connects the Oakland approach on the east with a self-anchored suspension span to the west, is only one component—but a major one. It consists of separate eastbound and westbound structures designed for five lanes of traffic each plus shoulders on both sides. Each structure has an overall width of 87.5 ft, a length of about 1.3 miles, and consists of four structural frames joined together by hinges that can transfer shear and moment while allowing longitudinal movement.

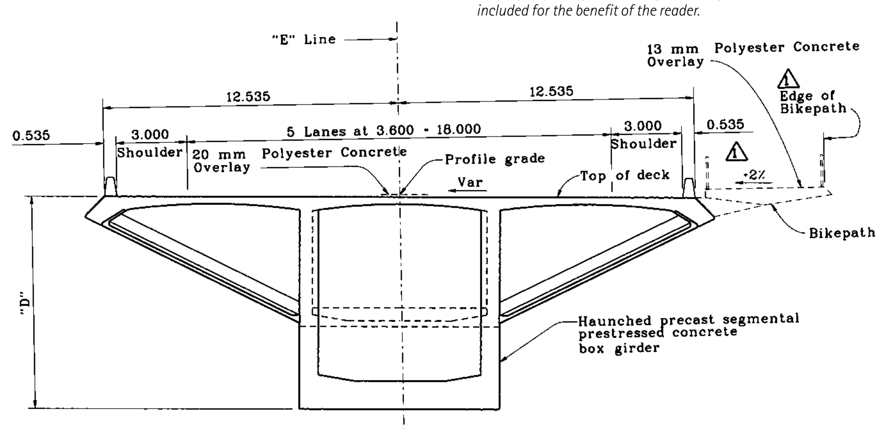
Designed for a 150-year service life, the Skyway has taken about five years to build. A section of the existing 1930s-era eastern span of the San Francisco-Oakland Bay bridge collapsed in the 1989 Loma Prieta earthquake, and the California Department of Transportation decided to replace it rather than retrofit the older bridge for seismic resistance. Preliminary design on the Skyway started in 1998, and the joint venture contractor, Kiewit/Flatiron/Manson (KFM), launched construction on February 6, 2002.

Largest Segments Ever

After consideration of baseline designs in both concrete and steel, concrete emerged as the least expensive material, says Sajid Abbas, project engineer for T.Y. Lin International in San Francisco, the bridge's designer. Each structure consists of a three-cell, variable-depth box girder built of huge precast concrete segments. "I believe these are the largest precast bridge segments cast anywhere at any time," said Tom Skoro, KFM project manager.

Seismically-resistant foundations are expensive to construct in the Bay mud, and foundation work accounted for about half of the bridge's $1-billion-plus cost. To offset the larger costs of the foundations, the balanced-cantilever method of construction was used for the superstructure. In this method, the variable depth segments were erected in both directions working outward from the piers. This method permitted span lengths up to 160 m (525 ft).* The depths

The Skyway Bridge was designed using SI units. Conversions are included for the benefit of the reader.



The Skyway segment is a three-cell custom design in precast concrete. Segments are 26.7 m (87.5 ft) wide and range in depth from 9 m (29.5 ft) at the piers to 5.5 m (18 ft) at the midspans.

SEGMENTAL PRECAST CONCRETE / CALTRANS, OWNER

REINFORCING STEEL FABRICATOR Regional Steel Corporation, Tracy, Calif., and Martinez Steel Corp. (Precast Segments) Harris Salinas Rebar Inc., Livermore, Calif. (Cast-In-Place Concrete)

BRIDGE DESCRIPTION A dual, 2.1-km (1.3-mile)-long parallel structure built using precast concrete segments erected in balanced cantilever with a typical span of 160 m (525 ft)

STRUCTURAL COMPONENTS 452 precast concrete segments weighing 300 to 800 tons each; 28 cast-in-place, post-tensioned pier tables, each 88 ft wide by 66 ft long by heights varying from 16 to 30 ft; cast-in-place concrete piers; 160 concrete-filled piles up to 350 ft long; and 28 steel footing boxes weighing 900 tons each

BRIDGE CONSTRUCTION COST $1.044 billion

A segment is loaded onto a floating barge that fits into a slip at the precasting yard. The big straddle carrier, used to transport segments around the precast yard, has wheels with a diameter of 11 ft.

of the section ranged from 9 m (29.5 ft) at the piers to 5.5 m (18 ft) at midspans. Most segments have a length of 8 m (26 ft). The use of longer span lengths increased the cost of the superstructure but reduced the number of spans and, therefore, the cost of the foundations.

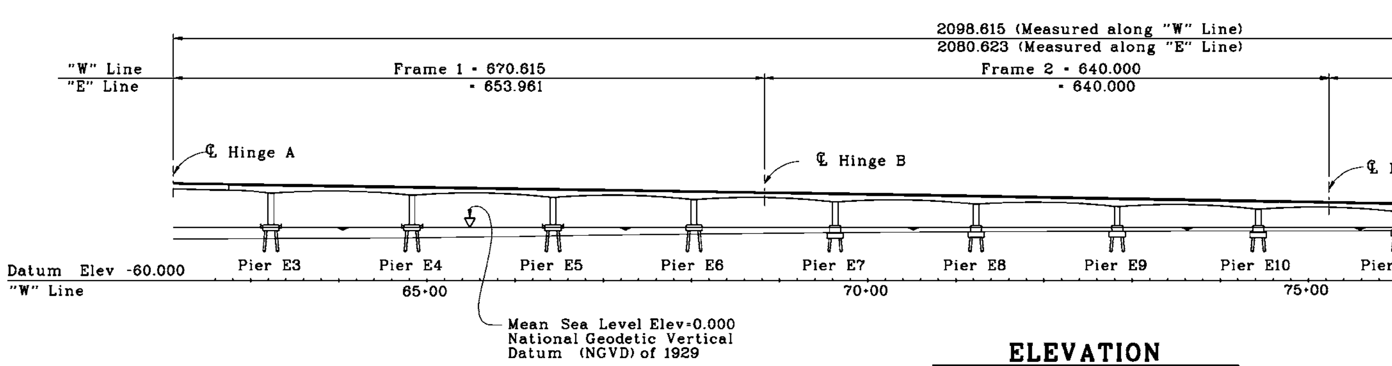
By contrast, span-by-span construction would have limited span lengths to about half the Skyway's 160 m (525 ft). That would have doubled the number of piers and made the bridge much more costly. On the other hand, Abbas notes, span-by-span construction for the superstructure would have been efficient because the segments would have a constant depth.

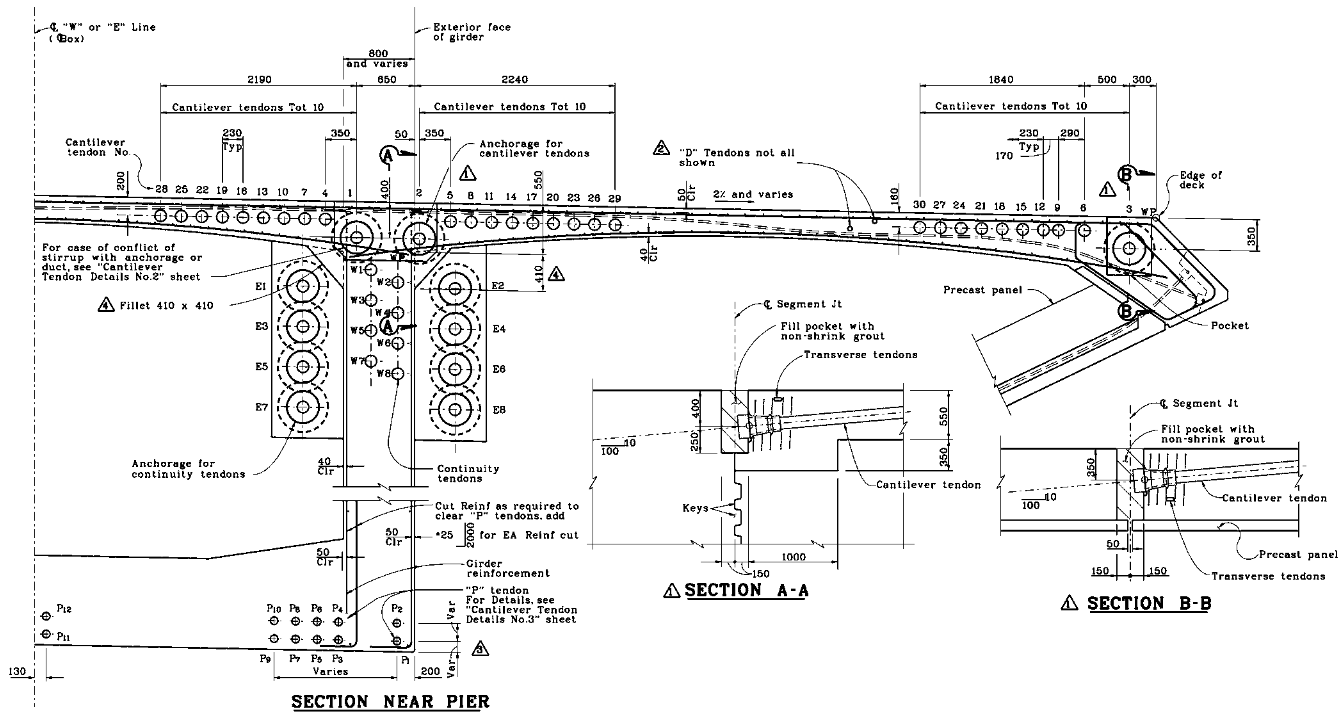
Designed In Four Frames

The Skyway is designed in four frames; three have four piers and one has two piers. The frames are typically connected at midspan by a large hinge consisting of twin steel-pipe beams, each 2 m (6.5 ft) in diameter and 20 m (66 ft) long. The pipe beams are supported in four diaphragms, two on each side of the joint. The hinges can transfer moment and shear while allowing longitudinal movement.

"The Bay mud shakes like a bowl of jelly during an earthquake," says Abbas. "The alignment places the bridge in deep Bay mud, and it is near two active faults—the Hayward Fault to the east and the San Andreas Fault to the west." "We designed a seismically robust structure. During a seismic event, the hinge pipe beams constrain the adjacent ends of the cantilevers to move together transversely, as well as act as seat extenders in the longitudinal direction, precluding any potential for unseating." The Skyway is designed for a Safety Evaluation Earthquake (SEE), which has a 1500-year return period, he notes. "The piers will take the brunt of an earthquake. The reinforced concrete piers are designed to behave in a ductile manner, and the rest

'We designed a seismically robust structure.'





A cross section of a half-segment near a pier shows the extensive post-tensioning used in the box girder.

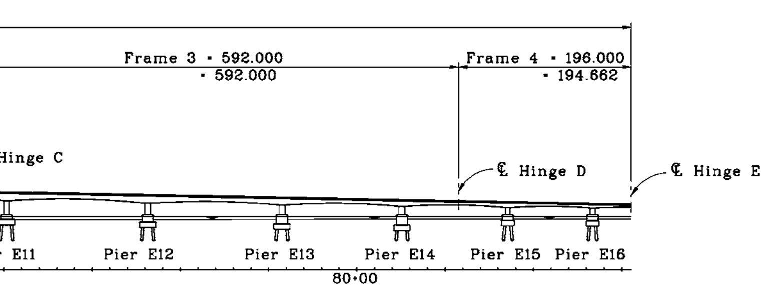
'I believe these are the largest precast bridge segments cast anywhere at any time.'

of the structure is capacity protected, which means it will see minimal damage during an earthquake."

During the SEE earthquake, the Skyway piers are expected to yield at the bottom, where they join the pile caps, and at the top, directly under the pier tables. "The inelastic response is controlled—the design criteria limit the maximum reinforcement strain in the piers during the SEE event to half of the ultimate strain," he explains. The cast-in-place reinforced concrete pier tables join the piers monolithically to the box girder. The piers themselves consist of four highly-confined corner columns joined by walls to create a hollow rectangular-shaped pier approximately 8.5 by 6.5 m (28 by 21.5 ft).

The superstructure box girder is stronger than the pier. "That way, yielding will not carry upward into the girder in an earthquake," says Abbas. The girder is designed with enough post-tensioning and reinforcing steel to resist seismic forces essentially elastically.

Similarly, the 28 pier tables contain heavy amounts of reinforcing steel to resist seismic forces. A typical pier table is 88 ft wide by 66 ft long, with heights ranging from 16 to 30 ft. Casting the pier tables required such massive amounts of concrete that KFM installed a water cooling system to reduce the temperature rise from the concrete's heat of hydration. In addition, the concrete contains a considerable amount of fly ash, which reduces the heat of hydration.



The 1.3-mile-long Skyway is divided into four frames separated by expansion joints that can resist both moment and shear. Three frames have four piers and one has two piers.

'There was heightened awareness about controlling the creep and shrinkage of the concrete as well as the modulus of elasticity.'

All reinforcing steel below a line 7 m (23 ft) above sea level is epoxy-coated to resist corrosion. That means reinforcement inside the 160 steel-lined piles is epoxy coated, as is the reinforcing steel in the pier caps and the lower portion of the piers.

Construction Challenges Abound

To complete the bridge, more than 190,000 cu yd of concrete had to be batched and delivered to the bridge for footings, access casings, piers, and pier tables. KFM worked closely with the concrete supplier, California Readymix, (a subsidary of RMC) to locate an on-site batch plant at Pier 7. The construction team developed concrete transport barges capable of handling 40 cu yd per barge, and the barges could deliver 70 cu yd per hour to the bridge, says KFM project engineer Paul Giroux.

At the bridge, concrete was conveyed from the transport barge to the placing barge, after which a conveyor took the concrete to KFM's barge-mounted 58-m (190-ft) concrete pump truck, from where it pumped the concrete to the desired location.

To cast the concrete segments for the big box girders, KFM built its own precasting yard in Stockton, Calif., about 70 miles from the construction site. All 452 segments were match cast at Stockton, stored for two to six months to reduce the effects of creep and shrinkage, and then barged to the bridge. The 55 acre precasting yard used two specialized long-line beds, a short line bed, and a hinged bed for the hinge segments.

The long-line casting beds could sequentially cast all the segments required for a complete half of a bridge cantilever, typically segments one through nine for each cantilever. The long-line bed consists of an inverted soffit system with adjustable geometry and a movable core that forms the interior voids of the segments, Giroux explains.

"In addition to the challenges of precasting the huge segments, we also faced a real challenge to develop and implement the necessary dimensional controls to ensure that all of the 452 segments would be match cast properly so they would all fit properly once erected in Oakland," says KFM's Skoro. "Further, as if the dimensional control challenges of the segment were not enough, our schedule dictated a three-day cycle for each segment in the casting bed."

Once segments were barged to the bridge, KFM used Self-Launching Erection Devices (SLEDs) to lift the segments into place on the cantilevers. The SLEDs are essentially computerized beam and winch systems, says Giroux. "The SLEDs are highly engineered, driven by the complexities of hoisting loads up to 800 tons from a barge that is subject to wind and wave action."

The SLEDs are anchored initially to the pier tables with 3-in.-diameter high strength bars. After a cast-in-place concrete closure placement is made between the pier table and the first segments and post-tensioned together, the SLEDs advance onto the leading segment where they are re-anchored. Then the next pair of segments are erected and post-tensioned together. The process then repeats, with the SLEDs advancing outward from the pier

At KFM's precasting yard, lightweight precast concrete sections for the sloping webs are placed before the remainder of the segment is cast.

Two Self-Launching Erection Devices (above the deck), which are computerized beam-and-winch systems, lift segments from barges into place on the cantilevers.

Designers faced the challenge of ensuring all 452 segments would be match-cast properly.

table until all nine pairs of segments of a typical cantilever have been erected. "When we are in full cycle working two shifts, each set of four SLEDs erected two segments per day," said KFM's Skoro.

High Strength Concrete Used

Normal weight concrete for the superstructure was specified to have a compressive strength of 8000 psi at 56 days. Lightweight concrete panels in the inclined webs of the segments were to have 6500 psi compressive strength at 28 days, says Abbas. In addition, the normal weight concrete was required to have a modulus of elasticity of at least 5160 ksi at 28 days, a specific creep not exceeding 0.52 millionths/psi at 365 days and a shrinkage not exceeding 0.045 percent after 180 days of drying.

"There was heightened awareness about controlling the creep and shrinkage of the concrete as well as the modulus of elasticity," says Abbas. Accordingly, segment concrete uses shrinkage-reducing admixtures, which can reduce initial shrinkage by as much as 40 to 50 percent and long-term shrinkage by 20 to 30 percent, depending on the dosage. For the pier tables, which contained a dense concentration of reinforcement, the use of self-consolidating concrete was considered, Abbas notes. However, when conventional concrete performed satisfactorily, Caltrans decided to stay with it.

To control the effect of shrinkage, the construction team used frame jacking within the four-pier frames, which have lengths of 691, 640, and 584 m (2280, 2112, and 1927 ft). Finally there is a two-pier, 188-m (620.5-ft) Frame 4. Once all cantilevers in a frame were erected and the closures in the outside spans were cast, KFM used a set of six jacks per girder web, placed at the location of the closure in the center span of the frame, to jack the two sides apart by about 4 in. using a load as large as 4000 tons. The central closure was then cast before the jacks were released.

"The intent is to compensate for long-term creep and shrinkage," says Abbas. "There was a total of six jacking operations in the entire bridge."

Not only is the bridge built "hell for stout," as contractors say, it's a handsome structure. Abbas notes that the architectural team was very active throughout design process. The architects requested that the shape of the girder's cross section match the steel section on the self-anchored suspension bridge to the west to provide a continuity of form.

The architectural team also was concerned with the shape of the piers, the look of the bike path on the north side of the eastbound bridge, and the light standards. That attention to detail added architectural interest to a bridge that already had structural engineers looking at it as if it were a thing of beauty.

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