Canadian Consulting Engineering Awards 2012 Submission

San Francisco Oakland Bay Bridge Construction Engineering

San Francisco, California

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PROJECT TITLE

San Francisco Oakland Bay Bridge Construction Engineering

LOCATION OF PROJECT

San Francisco, California

COMPONENT BEING SUBMITTED

Structural and geotechnical design of Temporary Works

CATEGORY OF ENTRY

Transportation

PROJECT CLIENT

American Bridge Fluor JV

PROJECT OWNER - TEMPORARY STRUCTURES

American Bridge Fluor JV

San Francisco Oakland Bay Bridge Construction Engineering

Submitted by: Klohn Crippen Berger

In 1989, the Loma Prieta earthquake caused a span of the San Francisco Oakland Bay Bridge to collapse, triggering the State of California to replace the bridge between Yerba Buena Island and Oakland. The eastern span includes four sections, the most significant being a self-anchored suspension (SAS) span. This signature suspension span will provide an iconic landmark for the City of Oakland and is already becoming a part of popular culture, being featured in movies, tourist brochures and on the logo for the Golden State Warriors.

The project was to become, in financial terms, the largest bridge project in history. The replacement span is engineered to withstand the largest earthquake expected over a 1500 year period, and it is expected to last at least 150 years with proper maintenance.

The Largest Self-Anchored Suspension Bridge in the World

The twin deck bridge will carry 10 lanes of traffic, a 5m wide walkway/bike path, and includes provision for future Light Rapid Transit. Once complete, the $1.8B span will have the distinction of being the world's largest self-anchored suspension bridge.

Unique in Design

The design features one 160m tower and uses a single suspension cable that to support the bridge deck. Normally suspension bridges have their cables anchored into the ground or massive concrete blocks at each end. Deck sections are lifted and suspended from the cable to be connected together. At this site, however, the end of the suspension span was in 20m deep water and another 100m of sediment over the Franciscan bedrock, so anchor blocks could not be used. Thus an uncommon structure type was chosen, a "self-anchored" suspension bridge, which requires the horizontal component of the suspension cable force to be resisted by compression in the deck. The deck must therefore be in place before the cable, so a temporary bridge-to-build-a-bridge was required to support the steel box girder segments until their weight can be transferred to the main cable. Due to the long period of exposure, approximately three years, the State included stringent seismic loading criteria for the temporary works design. The optimal design solution comprised a system of twin 600m long temporary steel trusses supported on seven steel tower pairs.

The Contractor, American Bridge Fluor Joint Venture, engaged Klohn Crippen Berger Ltd. (KCB) as Prime Consultant for the erection of the steel orthotropic box girder deck and the single steel tower. KCB performed all the structural and geotechnical engineering out of their Vancouver office for the twin 600m long temporary trusses and supporting towers required to construct the deck and the 163m high frame required to assemble the tower.

The site is located between the seismically active Hayward and San Andreas faults. With the 6-year construction schedule, and up to 3 years with the deck supported on the temporary structures, the exposure to earthquakes was a key design considered at every stage in construction. The twin trusses were supported on tubular eccentrically braced frame towers capable of absorbing and dissipating the earthquake energy and limiting the potential damage to the permanent structures should a large earthquake occur.

KCB also designed individual cradles on which the steel deck segments were placed. The cradles enabled the deck segments to be slid along the truss and were designed to enable fine adjustments to be made to mate the girder ends for connection. Highly complex staged analysis was required to determine the necessary movements accurate to within millimetres, to connect the deck segments. The single steel bridge tower required a 163m high braced frame and lifting gantry for placing the individual tower segments.

For the temporary works, a total of 25,000 tonnes of steel were designed to assemble the 65,000 tonnes of steel used in the permanent structure. To put this in perspective, the temporary works alone comprise more steel than was used to construct the new Port Mann Bridge and the Golden Ears Bridge combined. Upon completion, the temporary steel will be removed and used for other temporary works or sent back to the steel mills for recycling.

When constructing the temporary works, efforts were made to reduce the amount of waste and overall impact of the project. It was as high priority to modify and reuse as much material as possible for the temporary works. For example, the tower gantry was modified for use in the cross beam erection and then back to the tower. Bolted field connections were used rather than welded connections which produce less waste and reduce workers exposure to fumes and other hazards. Only the areas of the temporary works that were directly connected to the permanent structure were painted to protect the permanent structure from rust staining. The rest of the structure was left untouched to expedite the process of recycling the steel when removed.

KCB's deliverables for the project included over 1000 Issued for Construction drawings, 38 design reports required for submission to the State, and over 300 separate transmittals. KCB also undertook extra work tasks for the project requested and captured in over 60 separate Change Orders. ABFJV, who value the temporary works at approximately $350M, included an incentive clause in KCB's contract for savings in steel weight. Through design efficiencies, KCB was able to achieve savings of over 2,000 tonnes of steel from the weight used in the bid.

The State of California are in a race against time to complete the project before the next big earthquake strikes the Bay area, and meeting the schedule for the temporary works design and erection analysis was a critical requirement for the project. The temporary structures needed to provide all the support for the bridge, access for the construction activities, and even safety in an earthquake at any stage during construction. The design work was all completed on time and budget and the construction of the deck and tower have gone exceedingly smoothly. The cable is now being installed and the bridge is expected to open in mid-2013.

Prime Consultant

Klohn Crippen Berger

Contractor

American Bridge FLUOR

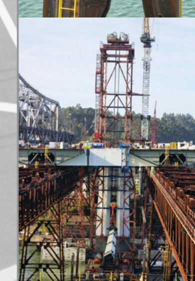
CANADIAN CONSULTING engineer

San Francisco – Oakland Bay Bridge East Span Replacement Project
Self-Anchored Suspension Span – Construction Engineering

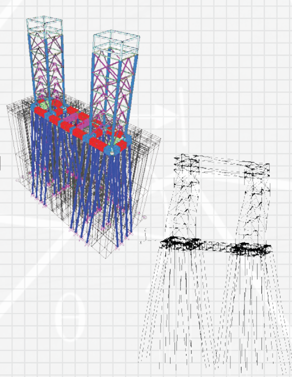
Largest Self-Anchored Suspension Bridge in the world

$1.8 billion span is the signature structure in the largest public works project in California history

- "Self-anchored" bridges require support of the deck on temporary structures for up to 3 years until the cable is in place
- Klohn Crippen Berger provided structural and geotechnical engineering for temporary works
- Temporary structures required design for a San Francisco earthquake, and accidental ship impact
- "Tubular Eccentrically Braced Frame" towers were designed to resist seismic loads, the first application of earthquake researchers' recent development

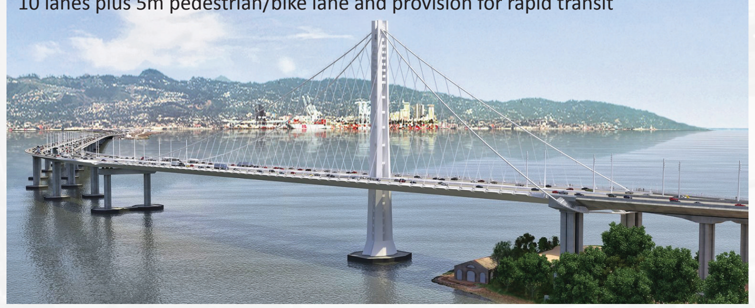


Tubular EBF Towers

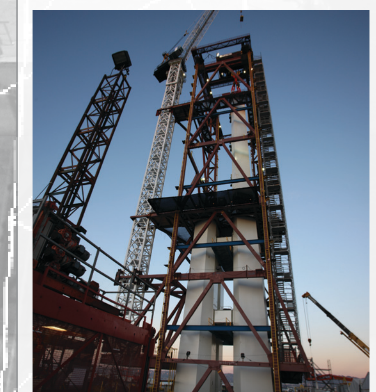


Tubular eccentrically-braced frames, used to improve the ductility and protect the permanent structure at all stages in construction.

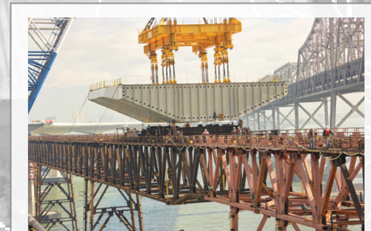
Rendering of completed bridge in 2013
10 lanes plus 5m pedestrian/bike lane and provision for rapid transit



Single steel tower required an independent temporary tower to lift the components into place



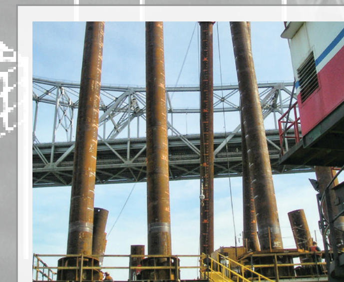
163m tower built with "self-climbing" crane



Staged analysis was required to verify structural integrity and geometry to tolerances within millimeters

25,000 tonnes of structural steel was required for temporary works, more than the new Port Mann and Golden Ears Bridge combined

Overland transport of marine foundation frame



Piled tower foundations in "bay mud" in 25m deep water

Photos courtesy of the California Department of Transportation

Executive Summary

The San Francisco Oakland Bay Bridge East Span is being replaced as part of the largest public works project in California history. The twin deck bridge will carry 10 lanes of traffic, a 5m wide walkway/bike path, and includes provision for future Light Rapid Transit. The $1.8B signature span will be the world's largest self-anchored suspension bridge, an unusual structure type in which the horizontal component of the suspension cable force is resisted by compression in the deck. Construction of this bridge type requires the deck to be supported on a temporary structure until the cable is installed and the deck weight is transferred to the cable.

The Contractor, American Bridge Fluor Joint Venture, engaged Klohn Crippen Berger Ltd. as prime construction engineer for the erection of the steel orthotropic box girder deck and the single steel tower. KCB performed all the structural and geotechnical engineering out of their Vancouver office for the twin 600m long temporary trusses and supporting towers required to construct the deck. The deck segments were placed on individual cradles that were used to slide them into position and make fine adjustments to mate the girder ends for connection. Highly complex staged analysis was required to determine the necessary movements, accurate to within millimetres, to connect the deck segments. The single steel bridge tower required a 163m high braced frame and lifting gantry for placing the individual tower segments. Large earthquake and accidental ship impact loads added significant complexity to the design of the 25,000 tonnes of temporary steel.

Rendering of completed bridge in 2013
10 lanes plus 5m pedestrian/bike lane and provision for rapid transit

Project Objectives, Solutions and Achievements

In 1989 the Loma Prieta earthquake caused a span of the San Francisco Oakland Bay Bridge to collapse, triggering the State of California to replace the bridge between Yerba Buena Island and Oakland. The project was to become, in financial terms, the largest bridge project in history. The signature element of the project now under construction is the $1.8B Self-Anchored Suspension Span (SAS), a spectacular 10 lane wide single tower suspension bridge.

The permanent bridge was designed by a team of consultants in San Francisco. Under the terms of the Contract, the means and methods for erection and all temporary structures, including their design and construction, are the responsibility and property of the Contractor. The joint venture of American Bridge and Fluor engaged Klohn Crippen Berger (KCB) to provide preliminary engineering during the bid in order to estimate the cost of the work. Subsequent to contract award in 2006, ABFJV engaged KCB to provide the structural and geotechnical engineering for the detailed design of the temporary towers and trusses required to construct the SAS deck and tower, along with all associated erection staging analysis.

$1.8 billion span is the signature structure in the largest public works project in California history

Normally suspension bridges have their cables anchored by massive concrete blocks at each end, and deck sections are lifted and suspended from the cable to be connected together. At this site, the end of suspension span was in 20m deep water, so anchor blocks could not be used. Thus an uncommon structure type was chosen, a "self anchored" suspension bridge, which requires the horizontal component of the suspension cable force to be resisted by compression in the deck. The deck must therefore be in place before the cable, so a temporary bridge-to-build-a-bridge was required to support the steel box girder segments until their weight can be transferred to the main cable. Due to the long period of exposure, approximately three years, the State included stringent seismic loading criteria for the temporary works design. The optimal design solution comprised a system of twin 600m long temporary steel trusses supported on seven steel tower pairs.

A key requirement of the structures was to facilitate manoeuvring of the deck and tower sections into position for assembly. A 1700 tonne capacity marine crane set the deck segments on independent "cradles" designed to limit reactions to avoid overstress of the bottom plates of the deck segments. The cradles and deck segments were then slid up to 220m horizontally to their final position. Sliding was accomplished using a stainless steel/teflon system on "slider supports" located at each truss work point. Fine movements in all 6 degrees of freedom, using mechanical jacking and shimming systems designed into the slider supports, provided for precisely positioning segments for connection.

Foundations were required for the temporary towers, with conditions ranging from steeply sloping bedrock on Yerba Buena Island, to deep soft marine deposits in 27m deep water under the main bridge span. Geotechnical design and field review services were provided for various foundation types including:

- Drilled micropile group foundations to facilitate construction on steeply sloping terrain

- 1574 mm diameter Cast-in-Drilled-Hole (CIDH) concrete piles drilled into bedrock
- 1067 mm diameter steel pipe pile driven into weathered bedrock in 15 m deep water
- 1220 mm diameter piles driven 40 m into marine clays in 25 m deep water

The suspension bridge tower, known as T1, is a single steel tower comprised of four individual interconnected legs. The 160 m tower, to be fabricated and erected in four segments per leg, was too high to be built with a marine crane. The solution was to construct a temporary braced steel tower, known as T1ET, constructed in stages in advance of T1 by a self-climbing crane. A lifting gantry, to be removed and placed on top of each subsequent T1ET stage, was designed to lift the tower segments and place them precisely in position.

The total weight of the temporary steel required for the work is approximately 25,000 tonnes, more than is in the original Bay Bridge. Fabrication of the steel took place in eight different fabrication facilities in various locations in North America and Asia.

KCB's deliverables for the project included over 1000 Issued for Construction drawings, 38 design reports required for submission to the State, and over 300 separate transmittals. KCB also undertook extra work tasks for the project requested and captured in over 60 separate Change Orders. ABFJV, who value the temporary works at approximately $350M, included an incentive clause in KCB's contract for savings in steel weight. Through design efficiencies, KCB was able to achieve savings of over 2,000 tonnes of steel from the weight used in the bid.

More steel was used for the temporary works than the Ironworkers Memorial and existing Port Mann Bridges combined

Technical Excellence and Innovation

The project bid documents included preliminary designs for individual towers braced both laterally and longitudinally, providing discreet non-continuous support to the girders. Subsequent to award, KCB developed an entirely new concept incorporating continuous trusses connected to the massive permanent bridge piers at both ends for longitudinal stability. This provided four major improvements in the construction methods for the self-anchored suspension bridge including:

1. Eliminating the need for longitudinal bracing of the towers
2. Allowing the towers at the east end to be supported directly on the permanent pile cap allowing elimination of four costly marine piled foundations.
3. Eliminating the need to make "mid-air" girder connections while supported by the marine crane
4. Facilitated convenient access routes for workers and equipment and solving onerous access problems for the Contractor

The large mass of box girders supported at 50m elevation gave rise to very high seismic demands. Eccentrically Braced Frames (EBF's) which incorporate a ductile (yielding) mechanism that dissipates earthquake energy providing a "fuse" to limit the seismic loads in the structure were a potential solution. However lateral bracing at the link work points are required for traditional EBF's meaning multiple horizontal diaphragm would be required at each link elevation.

Tubular EBF's that use rectangular box section links to eliminate the lateral bracing requirement are a recent seismic design breakthrough and the subject of extensive research at the University at Buffalo, NY, a leading US centre for earthquake research. KCB worked closely with the researchers to develop the first major use of tubular EBF's for the temporary towers. This proved to be a highly economical way to meet the stringent ductility requirements for the project. Their use is currently being referenced in papers by those same researchers to encourage industry acceptance for this efficient system.

Extensive analysis at all construction stages was required to verify structural integrity, and to determine the expected jacking loads and deflections for ABFJV to use in manipulating the deck segments to make connections. In order to advance the schedule, placement of the deck segments began when the temporary trusses were only partially complete, meaning the truss and deck structural configuration were both varying at each stage in the process.

The highly complex staged analysis was required to capture:

- The complex interaction between the continuous box girder and continuous supporting truss
- The effects of temperature and thermal gradients on the girders
- Planning the adjustments required, to tolerances within millimetres, to deflect the previously installed continuous deck in order to mate with the newly installed deck segment
- The 3 dimensional vertical curve camber fabricated into the box girders and cross-beams, requiring development of novel modeling techniques
- The 3-dimensional girder geometry to simultaneously mate both the girder end connections and cross-beam connections between the twin deck
- The load effects of the 42 girder segments being placed and some slid up to 220m slid along the truss, which required assessment of 104 stages progressive stages of completion
- Seismic analysis at each stage, including while the girders were sliding on the trusses

Over the course of the project over 200 computer models with up to 8000 elements each using four different software packages were developed, evaluating over 3000 load cases and combinations.

Environmental, Economic, and Social Sustainability and Aesthetic Aspects

The Bay Bridge is part of the 49 Mile Scenic Route which is a popular draw for tourists who wish to see what San Francisco has to offer. A design contest was held for the signature span and the final design was chosen for its visual impact and its ability to enhance the driving experience for local commuters and visitors. The signature suspension span will provide an iconic landmark for the City of Oakland. The eastern span is already becoming a part of popular culture, being featured in movies, tourist brochures and on the logo for the Golden State Warriors. The bridge carries over

280,000 vehicles per day and is an integral part of the economic development of the area.

The new bridge has a design life of 150 years and incorporates extremely robust seismic design measures to provide protection for the users, and a critical emergency route when the next big earthquake hits San Francisco.

The success of the construction of the new bridge required an effective and innovative approach to its construction. In addition, the falsework needed to be in place for several years and in the event of a major earthquake needed to be designed to protect the permanent structures from damage.

KCB's design of the temporary towers and trusses identified design efficiencies that:

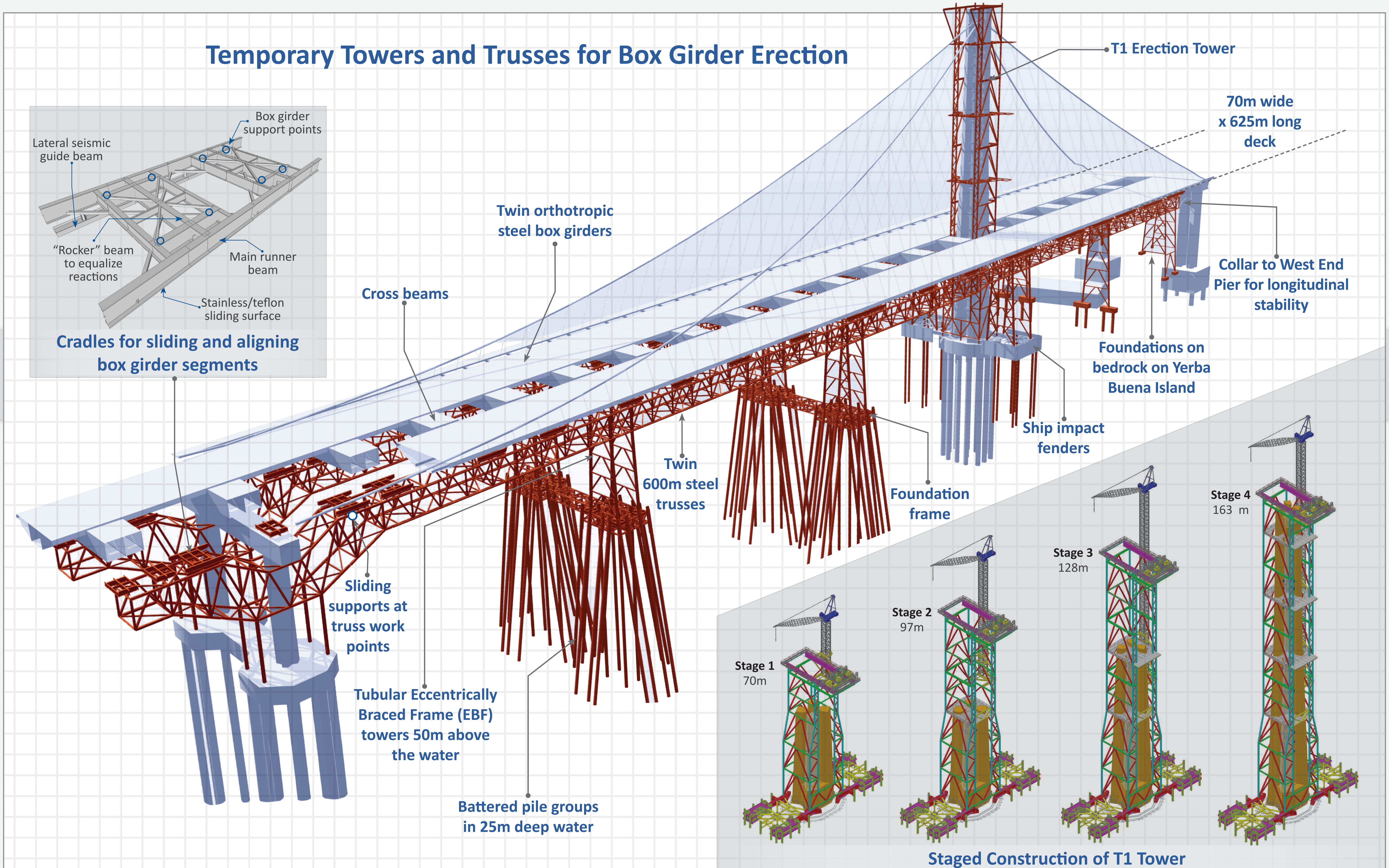
- increased the speed of construction of both the deck and the tower.
- reduced the amount of steel used for the temporary works by over 2,000 tonnes. The steel used for the temporary works will be recycled or reused.
- construction techniques were applied to reduce waste and impact of the project. Bolts were used instead of welding and paint was kept to a minimum applied only to areas where the temporary works connected with the permanent structure.
- advanced the science of bridge engineering in developing analysis methods and construction techniques for building of major bridges.

Conclusion

The State of California is in a race against time to complete the project before the next big earthquake strikes the Bay area, and meeting the schedule for the temporary works design and erection analysis was a critical requirement for the project. The temporary structures needed to provide all the support for the bridge, access for the construction activities, and even safety in an earthquake at any stage during construction. The design work was all completed on time and budget and the construction of the deck and tower have gone exceedingly smoothly. The cable is now being installed and the bridge is expected to open in mid-2013.

The Eastern span is featured in the Golden State Warriors logo

Temporary Towers and Trusses for Box Girder Erection



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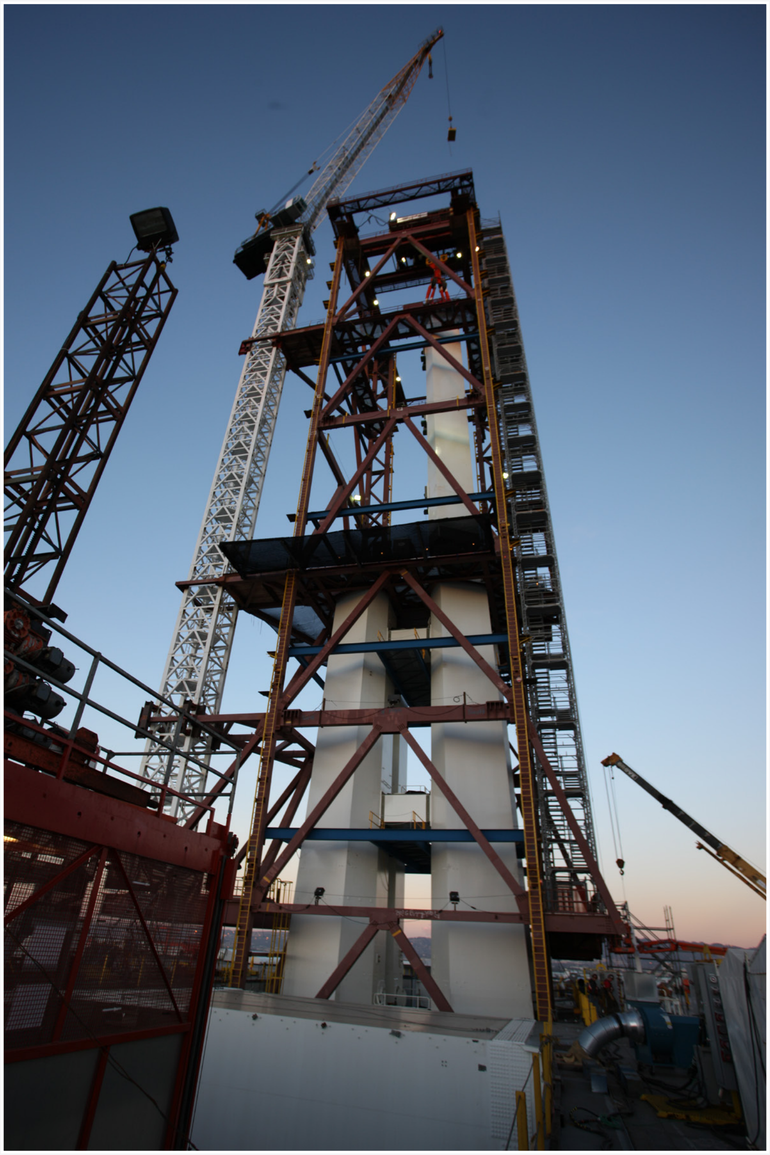

163m TIET tower built with “self-climbing” crane

Piled tower foundations in “bay mud” in 25m deep water

Staged analysis was required to verify structural integrity and geometry to tolerances within millimeters

Crossbeam connection - one of 47 individual segments lifted and connected

Completed tubular EBF tower on deep marine foundation driving frame

8.5m deep temporary trusses lifted and placed with marine crane

Klohn Crippen Berger