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BIG BAY BUILD

With the erection of temporary works for San Francisco's new self-anchored suspension span progressing, the contractor is ramping up for delivery of the first sections of deck. Helena Russell explains the challenges lie ahead

It may represent a relatively small percentage of the crossing in terms of length, but the 615m-long self-anchored suspension span being built in California in the USA is by far one of the most complex and demanding parts of the new east span of the Bay Bridge. And although construction of the bridge is well under way – at this stage largely temporary works – the means and methods for some of the most complex parts, the cable erection and load transfer in particular, are being finalised.

The main elements of the contract, which is being built by a joint venture between American Bridge and Fluor, are the tower and superstructure of the self-anchored span, along with two large cross-beams on the piers known as E2 and W2, at the east and west ends of the cable-supported spans respectively. The tower is a steel structure made of four shafts which are interconnected with shear links over its full 160m height, acting as fuses to protect the tower during an earthquake. The deck consists of two lines of steel box girders, one for each carriageway. These are connected by steel cross-beams at 30m centres. On the south side of the eastbound deck is a cantilevered pedestrian and cycle path.

When itemised in this way, the work seems relatively simple and yet it is anything but. For a start, the temporary works required to build the self-anchored span are significant – as ABFJV operations manager Brian Petersen explains, the team is effectively building a temporary bridge in order to build the permanent bridge. Huge steel piers and trusses are being gradually erected along the line of the self-anchored span, and these will be used to support sections of box girder deck until the cable and hangers are installed and the load transferred. In financial terms, it is the largest public works contract in the history of Caltrans; ABFJV's bid was US$1.43 billion when the contract was awarded in 2006.

The foundations, pier caps and columns of the adjacent piers were already in place or under construction when the JV started work in 2006, as were the foundations of the main tower. The W2 foundations on Yerba Buena Island were installed by contractor West Bay Builders and were finished about five years ago. The foundations and columns for pier E2 and the foundations for the main tower were built by a joint venture of Kiewit/FCI/Manson, which also built the skyway approach which was was completed in 2006.

Construction of the two huge cross-beams was the first major challenge on this section of the work – these are not standard elements on which bearings and deck elements will be supported – they also support the anchorages and saddles for the cable itself.

E2 is the point at which the anchors for the two ends of the single suspension cable will be located. The cable starts at the east end on the eastbound carriageway and goes over the tower then loops around the west bent after which it come back over the tower and back into the westbound roadway. Lead designer for designer of record TY Lin International/Moffat & Nichol JV Marwan Nader explains: "The cable is slightly deviated through the east saddle which sits on the side of the box girder. It then dives into the box girder where the 137 strands are anchored using anchor rods, in a grillage in the box girder.

At W2, meanwhile, will be the deviation saddles around which the cable will curve. Nader describes the system: "At the west end, the cable loops around the west concrete bent. The cable is looped via two large deviation saddles and is effectively under the box girder. There is a jacking saddle to balance the load in the cable."

Finalising the detailed design of these parts of the work has been complex, but ABFJV project director Mike Flowers says that now "it is a matter of getting those clarifications into the detailed shop drawings". But he is keen not to underplay the work that this involves. "The challenges of the east end have been significant," he says, "and the last four lifts of orthotropic box girder are just short of 5,000 shop drawings. The fact that the cable is anchored there provides complexity but it is significantly exacerbated by curve and camber geometry".

The inside of the cross-beams are dense with large-diameter reinforcing rods and post-tensioning cables, making the use of self-consolidating concrete obligatory. But the fact that the suspension span is curved on plan means that the upper surfaces of the cross-beams are sloped, and this was not an easy thing to achieve with this type of concrete.

Above: Rendering of the finished bridge. Pier E2 is at the centre of the picture, with Yerba Buena Island in the background, behind the main tower. Opposite: The Left Coast Lifter and the temporary works for the SAS span. The old bridge is in the background *(Department of Transportation/Bill Hall)*

"On E2 we made it as a single pour," explains Petersen, "and it has a 2% slope across the top. We had to put a form on the top of the beam formwork to create this slope. The concrete is very viscous which makes it easy to pour but difficult to shape," he says.

But at least the delivery of the concrete was made easier by the proximity of the skyway, which has been finished since 2007. A temporary bridge was installed between the end of the skyway and the cross-beam, then the trucks were simply driven along the skyway to the end, where concrete was discharged and pumped to the booms on the pier top. From the concrete plant to placement was as short as 35 minutes, says Petersen, and it was rare that it pushed the 90 minute mark. This operation – involving a 1,600m^3 pour – could have been much more complex had concrete had to be barged to the site.

The E2 cross-beam will have the box girder deck resting on top of it, while at W2 box girder deck butts up to the cross-beam and traffic will run directly on the cross-beam. The connection between the steel box girders of the main self-anchored span and the concrete box girders of the skyway is partway between E2 pier and its neighbour. W2 also acts as a significant counterweight to the uplift forces created by the cable.

Aside from the construction of the two cross-beams, much of the work on site at the moment relates to erection of the temporary towers and trusses on which the deck will be erected. The temporary works consist of two main parts – the piers and trusses which will support the deck units, and the 160m-high T1 erection tower which will be used to construct T1, the steel tower for the main SAS span, over which the cable will be draped.

Twelve integrated temporary towers - two at each of six locations along the line of the deck - and two lines of trusses, one for each line of box girders and each 700m long, will support the deck. These add up to some 3,834t of pier steel, 7,869t of truss and 4,005t of cradles on which the box girders will be installed. Naturally such a substantial structure also requires substantial foundations, and one of the first jobs for the JV was to install 56, 1.1m-diameter piles, a total length of some 3.4km and 32, 1.2m-diameter piles, a total length of 2.3km. The former are vertical piles, the latter are battered, and they provide not only lateral restraint, they also offer protection against possible ship impact. The steel driving frame – totalling 2,696t – also forms the pile cap at the three tower locations where piles were used – at two of them it forms the fender for ship impact protection, but at the main tower this is provided by additional concrete fenders. At the east end, the temporary works bear off the foundations for E2 while the two most westerly temporary towers are built on Yerba Buena Island itself.

The temporary trusses are substantial items, and are being installed using ABFJV's mammoth floating crane, the Left Coast Lifter. As well as being able to lift large sections of truss into place with ease, the LCL is an essential piece of plant for the erection of the permanent works. This 1,700t floating crane has been specially designed by and built for the project, combining a heavy-lift barge of 122m long, 30m wide and 6.7m deep with a 100m-long retractable self-erecting boom tied back to an A-frame. The crane has twin main hooks each with a capacity of 850t, an auxiliary hook of 100t capacity, and a whip hook of 10t capacity. In fact the width of the barge was tweaked to make it just a few inches shy of 100' (30.5m); any ship this width or greater needs a special permit to use the Panama Canal.

Designed by American Bridge, the barge was fabricated by US Barge in Portland, Oregon, and in April 2008 it was shipped to China where Shanghai Zhenhua Port Machinery Company – the same firm which is fabricating much of the permanent works for the bridge – fitted it with the custom-built shear-leg crane. Its second trans-Pacific journey ended in March of this year when it arrived at the Bay Bridge site. The crane had to be designed to be self-erecting because there was no crane on the west coast of America capable of the task.

The arrangement of the temporary works towers and trusses has changed somewhat since the original bid, explains Petersen, to give the site team more flexibility and to suit the conditions. In the original bid the JV proposed more temporary towers, but the final configuration ties back into W2, using its deadweight to balance some of the loads. This has offered savings in the size and quantity of foundations needed, and the number of bents required. By contrast, the truss was redesigned to be continuous throughout. Although requiring more steel, this will offer greater flexibility for the erection of the deck units, Petersen explains.

Specialist consultant Klohn Crippen Berger is the JV's lead consultant for the construction engineering of the bridge, providing complete structural and geotechnical design services for the temporary support towers and deck trusses as well as design of the self-climbing temporary tower that will be used to erect the main tower. ▶

Tower unit being fabricated on the rotating jig.

Schematic of the deck and tower erection *(Klohn Crippen Berger)*

► The temporary structures are designed to resist both seismic and ship impact loading, as they will be in service for several years. The seismic lateral load resisting system is the first application of tubular eccentrically-braced frames, which have been developed at the Multidisciplinary Center for Earthquake Engineering Research in Buffalo New York.

The box girder deck for the self-anchored suspension span is all steel. At the east end it is connected to the east concrete bent via large bearings and shear keys. At the west bent, however, the box girder anchors in to the west concrete bent with multiple prestressing tendons which are distributed along the perimeter of the orthotropic box girder. The Yerba Buena Island deck is a prestressed concrete cast-in-place box girder. It will be connected on the other side of the west bent with steel pipe beams which allow longitudinal sliding. The east end of the SAS will connect into the steel nose of the orthotropic box girder deck section with steel pipe beams – the final piece of the skyway to be lifted *(Bd&e issue no 36)*.

The most important limiting factors on erection of the box girder deck – and indeed on the temporary works erection – are the presence of the existing bridge, which eliminates any possibility of erection from the south side, and the depth of water. The weight of the 42 box girder segments range from 500t to 1,500t and installation involves placing them on individual 'cradles' which will also serve as sleds to slide the segments into place for splicing. KCB has carried out staged erection analysis to determine the jacking movements required to position the segments for splicing, and to verify that stresses in the system are acceptable.

The temporary truss spans are up to 100m long, and vary in size across the length of the site. At the west end, where the towers are fairly close together and the spans shorter, a shallow truss of just 6.5m depth is required. Just east of the main tower, where the spans become longer, the temporary truss is beefed up to 8m depth for most of the remainder. But at E2, a different solution was required. The reason for the different types of truss relates to the different support conditions – at the west end, the box girder deck butts up against the concrete cross-beam, whereas at the west end it sits on top of the cross-beam. An underslung truss will allow the box girder to be placed directly on to the cross-beam.

Erection of the box girder deck will involve a total of 28 lifts, 14 for each line of girder, as well as 19 lifting operations to install the cross-girders that connect the two boxes. The whole system of installation, involving the sleds that allow the girders to be skidded along the trusses, has been developed so that the LCL can install all the box girders. Without the ability to move the box girders in this way, the barge would not have been able to install those that need to be closest to the shore, due to insufficient water depth.

The sleds will be moved by a specially-designed pushing frame which has jacks with a stroke of 3.2m and which operate with a 10-minute cycle. The furthest distance that a box girder unit will have to be pushed is 190m, and the first 10 units that are installed will be moved in this way. Each cradle has jacking points so that once a unit is in position, its alignment can be finely tuned longitudinally and horizontally before being spliced to its neighbour. Connection is initially a bolted splice, followed by welding of joints,then more bolts.

The first delivery of box girder units from ZPMC's plant in Shanghai was originally due to arrive this autumn, but Flowers explains that the delivery date has been put back due to some delays at the fabrication plant. "We have had to overcome some welding problems in Shanghai that led to some of the work having to be done again, and we are currently working to complete this. We are hopeful that we will be able to ship the first eight orthotropic box girder sections before the end of the year," he says. The first shipment will carry eight box girder units, stacked two units high, as well as three cross-beams. From the ship they will be transferred to one of the JV's barges, which can each accommodate two units, and prepared for installation. Further deliveries are expected at two-month intervals.

A special lifting frame has been designed for the installation of the box girder units – it is fully adjustable to accommodate the fact that every unit has a different centre of gravity. Just as the installation of the units is on the critical path of the project, so is the adjustment of the lifting frame, which can be a complex procedure. To remove this procedure from the critical path, a special stand has been designed on which the frame is placed and the adjustment carried out without the need for the LCL to be used.

The main suspension tower is a single tower with four individual shafts, connected with shear links designed to provide energy-absorbing plastic deformations during a major earthquake. The shafts of the 160m-high structure are formed of stiffened, pentagonal steel box sections which taper from bottom to top and have diaphragms spaced at 4m centres. The shafts are rigidly connected at the top and bottom by the tower saddle grillage and tower base grillage respectively. The shear links enable the bridge to meet its 'lifeline structure' behaviour, which requires it to remain functional after a safety evaluation earthquake for use by emergency services. They are designed so that they can be easily replaced if necessary, while under service loads they provide the tower with the stiffness it needs.

Sections of the tower will be shipped by lift, each of the four shafts as a separate piece, and transported horizontally. Each lift of the four shafts will be an individual piece, the maxiumum weight being the pieces for the first lift, which will be approximately 1,100t each. The shaft sections for lift two each weigh about 490t, for lifts three and four they are each about 450t. At lift five the tower head is erected, it is a single piece which ties the four shafts together and will support the tower saddles – it will weigh about 450t.

Klohn Crippen Berger provided structural design for the 163m-high braced steel temporary tower which will be erected around the main tower. A Favco crane, which is commonly used on building projects, will be installed on the temporary tower but is only expected to be used for the struts and bracing, not the main shaft units, even though it is capable of doing so. The temporary tower also has a lifting gantry which will house twin 660t-capacity strand jacks which will be used to lift the main segments of the tower.

The fabrication work for the steel elements for the main tower and deck segments, as well as much of the temporary works, is being carried out by ZPMC. Each deck lift will be made up of one, two or three segments, the sizes of which are determined by ZPMC to suit its fabrication facilities. ABFJV specifies the size of the lift and the splicing locations, but it is up to the fabricator to decide how these units are made up. Tower shaft segments are fabricated on huge rotating jigs, dubbed 'rotisseries', which allow the enormous units to be handled with minimum effort ■

CABLE CONUNDRUM

The path of the almost 1.4km-long single cable is a complex one to begin with, having to accommodate the combined problems of being a self-anchored structure with a single tower. This means that one end of the cable is anchored at the edge of the easternmost end of the self-anchored span, before sweeping upwards and inwards to the saddles at the top of the single tower, which sits in between the two box girders. From here it continues to the western end, where the deviation saddles are located, again sweeping downwards and back to the outer edge of the deck.

After curving under and around the deviation saddles at the end of the two box girders it begins its route back to the eastern anchorage, up over the saddles on top of the tower and down again to the edge of the deck.

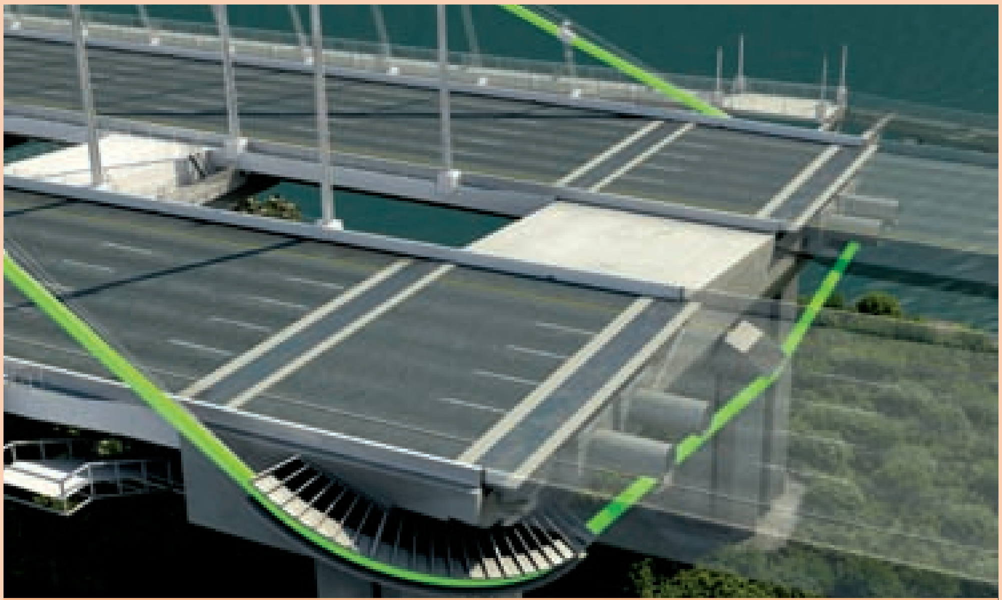
The single cable will be made up of 137 PWS strands, each of which will be almost 1.4km long and will contain 127 individual wires each 5.4mm diameter. Because of the geometry of the cable, the difference in length between the shortest and the longest strand is something in the order of 2m. At the saddles these strands must have a square cross-section in order to keep them in the correct alignment, while away from the saddles they will have a more traditional hexagonal cross-section.

The cables are being fabricated by Shanghai Pujiang Cable Company, using a new 'profile modelling' concept to 'pre-shape' or 'pre-bend' the strands to reduce the stress-differential between the wires (*Bd&e issue no 55).* Strands will be delivered on individual coils, weighing approximately 35t each.

To hold the square cross-section of the strand during installation, a strand clamp will be used at two locations on each strand, at the points where it enters or exits the deviation saddle. The strands cannot be nested, instead it is necessary to calculate the point-to-point configuration of each of the strands individually and ensure that they are installed to match this.

Saddles for the cable are being manufactured by the Japan Steel Works; three sets of saddles in all, for the tower, the east end and the west end. A jacking saddle is also required for the west end, which will be used during the load transfer process. They are being manufactured in several pieces, each of which weighs approximately 110t; some are cast and some are fabricated steel. In total, the tower saddle will weigh 450t – it will be a single saddle with two troughs. At the east end there will be two saddles and at the west end, three including the jacking saddle.

A total of 114 cable bands is being manufactured by Goodwin Steel Castings in the UK, and these each incorporate two grooves in which the pairs of suspender ropes will sit. But as ABFKJV operations manager Brian Petersen explains, even designing these relatively small elements has been tough. The geometry of the main cable and the fact that the suspender ropes have to link from the main cable to the outer edge of the deck, means that the angle and alignment of each channel has to be considered separately to ensure that the suspender ropes are all correctly positioned. Among the 114 bands there are 15 different types of band, each one based on the slope geometry of the cable at a specific point. When the load transfer occurs and the cable moves from being free-hanging to being loaded, it will undergo rotation as well as translation. Design of the geometry of the cable bands and the grooves for the rope also has to take account of this.



Schematic of cable deviation saddles and cable articulation at the west end *(TY Lin International)*

Suspender ropes themselves – fabricated by Wireco World Group in the USA – vary from 4m to 207m in length. The majority – 176 of the total 200 – will be 75mm diameter rope, while the remainder will be 90mm diameter.

Additional protection for the cable will be supplied by the use of s-wire wrapping from Nippon Steel Corporation. This product was first developed for use on suspension bridges in Japan, and was also used on the new Tacoma Narrows Bridge in Washington state. The wire has an s-shaped cross-section and is 3mm deep by 7mm wide – it is designed to be wound over the cable, and to interlock in order to prevent moisture from entering the cable. A total of 236 coils of the wire are estimated to be needed, each of which weighs 300kg.

As much of the cable erection as possible will be carried out using standard methods – consultant for this procedure is Arne Roen, whose experience includes air spinning the second cable on the Tagus River Bridge in Portugal, as well as Carquinez and Storebaelt.

Before erection of the cable even begins, the tower top will be pulled 0.5m westwards, towards the deviation saddle, and tied back to a temporary anchorage on Yerba Buena Island. As with construction of traditional suspension bridges, this is a correction which will ensure that the tower top returns to its upright position once the load transfer takes place.

A catwalk will be installed along the path of the cable, which will provide access for the erection of the PWS strands. Above this, a tramway will be built to provide the means for hauling the strands into position. Once a strand has been hauled the full length of the cable, it has to be properly positioned at each anchor. The strand is then shaped into the appropriate cross-section, and clamps are applied to restrain it.

At the anchorage and tower saddles, this will be a fairly straightforward procedure, but at the deviation saddle it is much more complex. As the strand is hauled around the deviation saddle, it will run on a series of rollers which are temporarily installed above the saddle. With hauling complete, clamps will be applied to the strand each side of the saddle, and it will then be connected to a restraining system which will allow it to be pulled out from the rollers and lowered down towards the saddle.

Once at the correct location, the restraining system is released gradually, starting at the midpoint between the two edges, and working outwards from there until the strand is correctly positioned.

The intention is to haul the strands from the northern anchorage, over the tower and down to the deviation saddles at the west end, then back over the tower and down to the south anchorage.

Compaction of the cable will be carried out using six 300t jacks working at 40% capacity for a resulting pressure of 720t to form the circular cross-section that is required. Cable bands will then be bolted into place and the suspender ropes installed over the cable bands.

At this point, the load transfer procedure will begin. The contractor is anticipating that the main cable will need to be translated down by up to 4m and transversely by up to 9m as it is pulled into its final alignment. The intention is to use temporary equipment to pull the cable out to this alignment before installing and tensioning about half of the suspender ropes – the locations of which will be carefully specified. At this point, the temporary truss will still be in place below the box girder deck, but it will then be removed before a second set of suspender ropes is installed and tensioned – including those close to the tower and to the eastern end of the deck.

The third phase involves installation and tensioning of the remaining suspender ropes. As well as the s-wire wrapping and other more traditional corrosion protection measures, the cable of the new SAS span will have a dehumidification system fitted.