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FABRICATION AND CONSTRUCTION OF SELF ANCHORED SUSPENSION BRIDGE SAN FRANCISCO OAKLAND BAY BRIDGE

M. Nader[1], J. Duxbury[2] and B. Maroney[3]

ABSTRACT

The signature span of the new Eastern Spans of the San Francisco Oakland Bay Bridge is an asymmetric Self Anchored Suspension (SAS) Bridge. The SAS spans a total of 565 m, with a 385m main span and a 180 m back span. Dual steel box girders are suspended from an inclined cable system supported on a single tower. The tower is comprised of four steel shafts inter-connected with shear links along its height. The unique configuration of the SAS presented challenges in the fabrication and construction. Unlike a traditional suspension bridge with parallel cables anchored into the ground, the SAS has a single 3-dimensional cable that is anchored into the east end of the box girder, passes over the tower top, and loops around saddles at the west pier. Each Parallel Wire Strand (PWS) has its own anchorage, which is detailed into the framing that transmits the entire cable force into the box girders. Because the cable tension is carried by the box girders, it was necessary to erect a temporary bridge to support the box girders during their erection, and then to construct the cable on the completed girders. During load transfer from the falsework to the suspension system the bridge compressed by 300 mm, requiring advance positioning of the tower top, the box girders, the bearings and the cable bands to fit the final geometry.

Geometric control of the fabrication and construction went from the global level to the detailing, and throughout the stages of erection. Surveys at the fabrication yard and on site monitored the tower shaft plumbness and twist, box girder cambers, cable band twists, suspender inclinations.

This paper discusses the challenges faced by the Design team, the Contractor and the Owner, and innovative solutions that were developed during the construction of this unique structure.

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Fabrication and Construction of Self Anchored Suspension Bridge San Francisco Oakland Bay Bridge

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The signature span of the new Eastern Spans of the San Francisco Oakland Bay Bridge is an asymmetric Self Anchored Suspension (SAS) Bridge. The SAS spans a total of 565 m, with a 385m main span and a 180 m back span. Dual steel box girders are suspended from an inclined cable system supported on a single tower. The tower is comprised of four steel shafts inter-connected with shear links along its height. The unique configuration of the SAS presented challenges in the fabrication and construction. Unlike a traditional suspension bridge with parallel cables anchored into the ground, the SAS has a single 3-dimensional cable that is anchored into the east end of the box girder, passes over the tower top, and loops around saddles at the west pier. Each Parallel Wire Strand (PWS) has its own anchorage, which is detailed into the framing that transmits the entire cable force into the box girders. Because the cable tension is carried by the box girders, it was necessary to erect a temporary bridge to support the box girders during their erection, and then to construct the cable on the completed girders. During load transfer from the falsework to the suspension system the bridge compressed by 300 mm, requiring advance positioning of the tower top, the box girders, the bearings and the cable bands to fit the final geometry. Geometric control of the fabrication and construction went from the global level to the detailing, and throughout the stages of erection. Surveys at the fabrication yard and on site monitored the tower shaft plumbness and twist, box girder cambers, cable band twists, suspender inclinations. This paper discusses the challenges faced by the Design team, the Contractor and the Owner, and innovative solutions that were developed during the construction of this unique structure.

Introduction

The seismically vulnerable East Span of the San Francisco-Oakland Bay Bridge is being replaced with a dual east bound and west bound 3.6 km long parallel roadway structure. The signature span consists of a Self-Anchored Suspension bridge (SAS), situated between the Skyway and the Yerba Buena Island (YBI) Transition. Some of the resulting unusual features of this structure presented challenges to the Design Joint Venture (T.Y. Lin International / Moffatt & Nichol Engineers), the Contractor (American Bridge Company / Fluor Enterprises Inc., A Joint Venture) and the California Department of Transportation. This paper discusses some of those challenges and the innovative methods that were developed during the construction of this unique structure.

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Four distinct structures will make up the bridge crossing: a low-rise post-tensioned concrete box girder near the Oakland shore; a 2.4 km long segmental concrete box girder (Skyway); a self-anchored suspension signature span; and a post-tensioned concrete box girder that connects to the east portal of the Yerba Buena Island tunnel (Fig. 1).

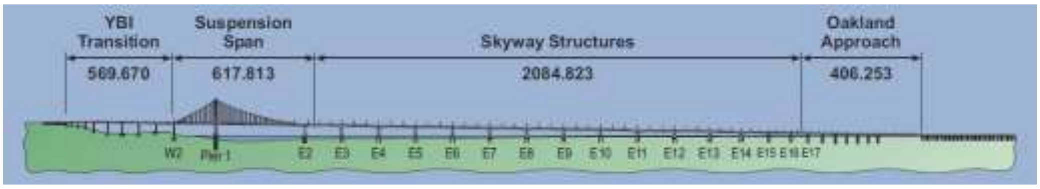

Figure 1. The new San Francisco Oakland Bay Bridge

Self-Anchored Suspension Bridge

The Self-Anchored Suspension (SAS) portion of the new East Span of the San Francisco-Oakland Bay Bridge consists of dual box girders suspended from cables which are supported on the 160 m tower located off of the eastern shore of the Yerba Buena Island. The SAS spans 565 m between the piers E2 and W2, with a 385m main span, over the navigational channel, and a 180 m back span (Fig. 2).

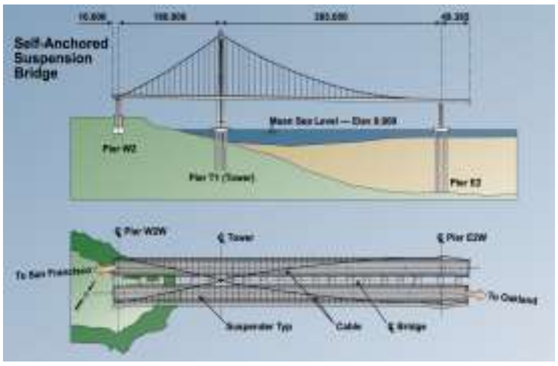

Figure 2. Elevation of the SAS

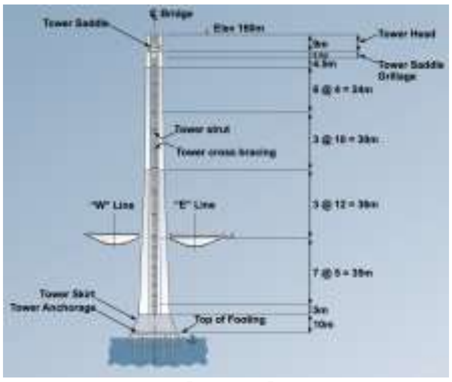

Figure 3. Single steel tower

The 160 m main tower is composed of four shafts interconnected with shear links along its height. Seismic performance is enhanced by the redundancy of four shafts to support the bridge's full vertical weight, and by the cross-braces and shear links that tie the shafts together and provide redundant horizontal framing (Fig. 3).

Superstructure

The superstructure consists of dual hollow orthotropic steel box girders (OBG) (Fig. 4). These girders are in longitudinal compression (reacting against the cable tension force) and are a part of the gravity load system. The box girders are connected together by crossbeams that carry the transverse loads between the hangers (span of 72 m).

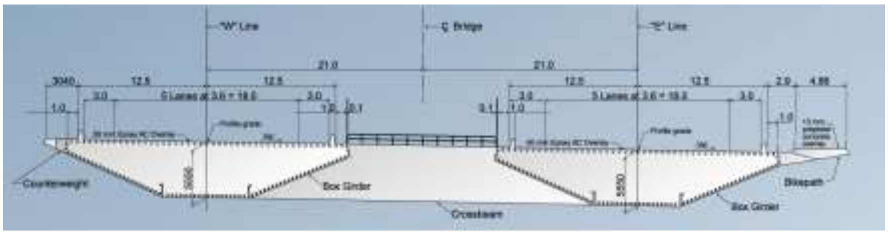

Figure 4. Typical bridge cross section box girders with cross beam

Suspension System

The configuration of the main suspension cable arose from key aesthetic and structural considerations. Strands of the single main cable are anchored inside the two box girders at the east pier. The cable then passes over the tower top, through one side of the twin-trough tower saddle. The cable loops below the deck at the western pier, and returns over the tower to the east anchorage (Fig. 5). The Hangers consist of two wire ropes looped over a cable band, and anchored into a bracket on the box girder by threaded rods into the rope sockets. The hangers are spaced at 10m and lie in two sloping planes. Within each plane all hanger ropes are parallel and exert no longitudinal force with respect to the deck girders or cable (See Fig. 15).

Figure 5. Three-dimensional cable

Expansion Joint Pipe Beams

The hinges in the transition spans between the SAS and Skyway as well as the SAS and YBI structures are designed to allow the structures to move relative to each other in the longitudinal direction and to rotate about the longitudinal axis of the bridge. The hinges are comprised of compact steel beam pipe sections capable of transferring live loads and seismic loads (See Fig. 20). The Skyway was built under a separate contract. The construction engineering for the alignment and the final connection of the two structures is described below.

Erection of the Bridge

In a classic suspension bridge design, the entire design dead load is assumed to be carried by the suspension system, while the stiffening trusses or girders only serve to distribute live loads and limit local deflections. The stiffening system typically has very small bending moments under the design dead load. The hangers are typically vertical, and the longitudinal component of cable tension is a constant. The suspension cable and hangers are erected first. The deck segments are then hung from the hangers and little falsework is needed. Erection is facilitated by the following factors: 1. The suspension system supports the deck during erection; 2. The hangers are vertical; 3. The deck segments have no dead load moments built into the construction.

In the SAS these conditions do not apply. Since the box girder maintains the tension in the cable, it must be erected on falsework prior to the cable erection (Fig. 6). Given the sloping hangers, it is a highly indeterminate problem to find the profile of the suspension system hangers, even when the hanger supports don't move. Due to the support conditions at the end piers there are moments in the box girders throughout the length of the bridge, and these are determined by design.

Figure 6. Temporary truss falsework

The consideration of the dead load moments that are built into the deck segments is described below.

Traditionally, cable supported bridges are analyzed “backwards”, starting from their intended final configuration, to find the necessary initial conditions from which to base construction. Particularly with respect to the cable, this technique was employed for the SAS. The main analysis of the SAS has been a “forward” analysis, however, starting from known, or computed, initial conditions. This has facilitated determining critical steps in the construction, evaluating alternative methods of erection, and tracking the progress of the construction. The analysis and the erection control considered the staged construction of the bridge in great detail, including the following major steps: 1. Box girder erection; 2. Tower erection; 3. Cable erection; 4. Hanger installation; 5. Connection to the Skyway; 6. Addition of superimposed dead load.

Tolerances and Geometry Control during Fabrication and Erection

The unusual layout and supporting system of the SAS required fabrication to close tolerances within the controlling interfaces of the following locations: the foundation piers, the connection to the adjacent Skyway, and the entry of the main cable into the orthotropic box girders (OBG). It is important to realize that all points on the superstructure, except for the foundation connections, were initially erected at other than their final positions. This fact required extensive erection analysis both before the construction, as well as in response to unanticipated field conditions.

Fabrication of Box Girders

The geometric control started during fabrication in China and was continued on site in San Francisco. The cambered geometry of the three-dimensional girder model was projected onto the shop floor in the total station set-up of the fabrication jigs, which set the lower faces of each girder segment. The geometry of the floorbeams and upper faces were controlled from the lower faces (Fig. 7).

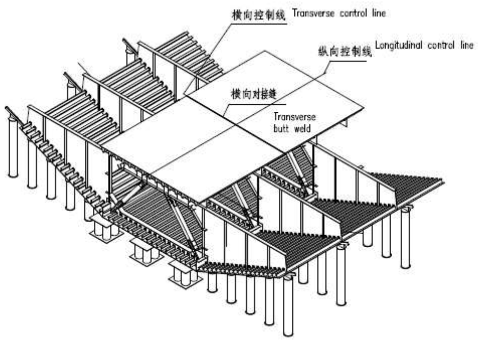

Figure 7. Box girder fabrication

Figure 8. Tower foundation

Fabrication of Tower

The tower shaft segments, lying prone, were similarly assembled from surveyed jigs. For the base of each shaft it was necessary to ensure that all of the 574 anchor rods and dowels in the tower foundation in San Francisco would match the holes fabricated into the tower base plates. Fig. 8 shows the tower foundation. The chosen solution was to survey the as-built foundation and to fabricate a steel template in match-marked quarters. From the survey the holes were cut in the template, which was fitted onto the actual foundation prior to shipping to China. The template was matched to the four tower shaft bases to control the coring of the holes for the foundation connections.


Figure 9. Tower tier trial fit-up

When the tower segments were fabricated they were trial assembled over the tower base template, aligning all the holes, and then the shear link connections between each segment were fit up and match drilled. Once the four segments of each tier were assembled, adjacent tiers were placed one on the other for trial fit-up of the segment splices between tiers (See Fig. 9). The splice plates for the tower splices were match drilled in position. This geometric control facilitated alignment and assembly on site.

Alignment of East Saddle Grillage

The East Saddle Grillages transfer and distribute cable forces from the east saddles to the box girders, through a framework of connected plates with thicknesses varying between 75mm and 100mm. The grillage comprises five plates parallel to the saddle base plate, three plates in the plane of the transverse floorbeams, and two plates tying the grillage to a longitudinal supporting member (Fig. 10). The plates are connected to each other and to the box-girder through full penetration welds. The detailing of the saddle grillage plates was based on the cable geometry, so as to transmit the various components of the saddle bearing forces into the girder. Given the magnitude of these forces,

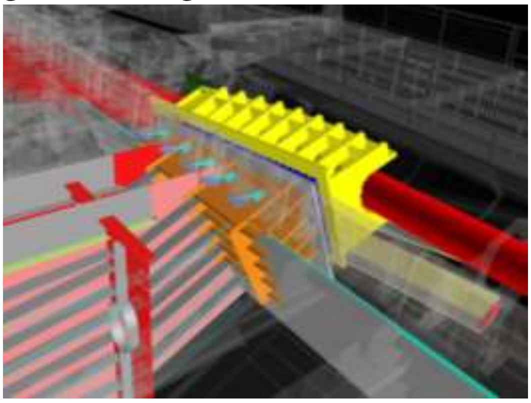
Figure 10. East saddle grillage

tolerances for the alignment were specified, and a full-size mock-up of the grillage was fabricated to verify welding and inspection access, and to establish a welding sequence that would minimize distortion and meet the tolerances.

Dead Load Camber

In the design of the SAS dead load moments were built into the girder, in order to reduce compression in the top fiber of the box girders (Fig. 11). These dead load moments were developed in the girders during SAS fabrication and erection by use of a downward “dead load camber”, which results in forced upward flexure of the boxes during erection. The dead load vertical camber is the deflected shape of the girders that results from the moment diagram, in the absence of all other loading. Each girder was fabricated with the camber shown in Fig. 12. The actual fabricated shape of the girders was determined by the combination of the final grade line and the dead load camber. The cambered shape was obtained by detailing small angle breaks between segments of the box girder.

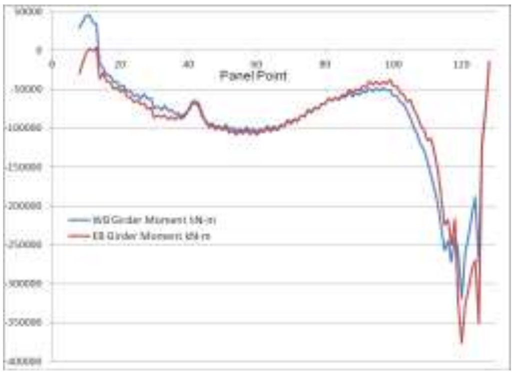

Figure 11. Girder dead load moment

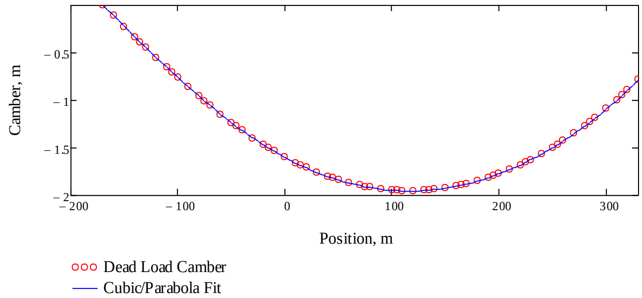

Figure 12. Dead load camber

Orientation of Box Girder Splices

During the fabrication the segments were constructed as straight segments of 20-25 m in length. As segments were constructed they were aligned and surveyed in the fabrication yard to implement the camber profile. The ends of each segment were trimmed to the alignment angle, and the bolted stiffener splices were fit up and match drilled. During the erection on site the segments were erected on falsework and oriented by jacking to align the bolted splices. Starting at the west end, the girder was aligned to the final profile grade and connected monolithically to the concrete pier. The camber shown in Fig. 12 is downward sag, and if the west end of the camber profile (left in the figure) is aligned to level, it can be seen that the girder in its cambered shape would rise significantly. For this reason, as the segment splice bolting was sufficiently complete each segment was lowered to its final profile, thereby introducing the Dead Load moments into the girders.

Erection of the subsequent sections and partial bolting advanced as welding proceeded on the skin plates of the previous girders. Partial bolted splices were completed with temporary bolts, and about half of the box perimeter stiffeners were left unbolted to facilitate the welding. After welding was complete on each girder face, the permanent bolted splices were installed, allowing for the removal of adjacent temporary bolts, until the perimeter splicing was complete.

Girder Length Control Surveys

In addition to the vertical camber, a dead load axial camber was also provided. Axial camber consisted of detailing the box girders longer than the final erected length. The axial compression strain on the box girders, resulting from the cable tension, was computed to be about 300 mm over their length during cable erection and load transfer, and these calculated strains were included in the fabricated girder geometry.

During the erection on site, the leading edges of the constructed girders were surveyed. Due to fabrication and erection tolerances, and shrinkage in the field welds, the cumulative length error in the first half of the total girder span was determined. The last three lifts leading up to the eastern pier were corrected for length as their fabrication was completed in China. The error that was measured and projected to the end of construction was divided among these three lifts. Excess length (green) that was detailed into each segment allowed this to be done. When the bearings at the east end of the main span (pier E2) were installed after load transfer, the alignment error was only 5 mm over the 565m distance between piers W2 and E2.

Tower Erection

The tower shafts were erected one segment at a time. Starting at the base each shaft segment was placed on the tower foundation. The use of the tower template ensured that each of the anchor rods and dowels entered its hole in the tower base. The four shafts in the first tier were aligned and plumbed on the temporary blocking prior to grouting. With the base aligned the assembly of the remaining segments followed the pre-drilled splice formed in China.

Tower Tie-Back

The main cable is supported on the top of the tower in a cable saddle. As in other suspension bridges, the saddle tends to move during the erection of the suspended structure. Therefore, the tower saddle was diverted 0.5 m towards the side span from its final, vertical position by tying back the tower. Fig. 13 shows the stay cables used to tie-back the SAS tower. These stays were anchored in the ground on Yerba Buena Island, and gradually released during the erection of the box girder to minimize the tendency of cable strands to slide through the tower saddle. The forces in the stays were reduced in each step of the analysis in accordance with the erection schedule

Figure 13. Tower tie-back

Main Cable Strand Erection Tolerances and Control

Cable and Hanger Length

The geometry of the main cable is determined by the final configuration of the bridge under dead load. This configuration includes the final grade of the box girder, the total weight of the box girder, and the horizontal component of the force in the cable, which is set by the design. The geometry of the cable and the forces in the cable and the hangers were computed to satisfy equilibrium of the structure. The final geometry of the bridge and the forces locked into the bridge are determined by the fabricated lengths of the cable and the hangers.

Great care was taken in the weight take-off of the fabricated structure. All components that were to be included in the final structure were tracked, including the rolling tolerance on the thickness of the plates used to fabricate the structure. Through a survey made in the fabrication shop by use of ultrasonic thickness gauges, it was determined that plates were on average 2% thicker than specified. This factor was considered in the weight take-off. For the SAS accurate weights are required, since the cable is anchored into the box girders, which compress under additional load, and this affects the cable final geometry.

Cable Displacement

The suspension cable was erected as a free-hanging cable (FHC), in order to have good compaction. The parallel wire strands (PWS) of the cable were towed by means of a tramway system around the path shown in Fig. 5. It was determined that the cable would then move over 9 meters from its initial to its final position, when the inclined hangers are attached and fully loaded. These movements are illustrated in Fig. 14, which shows both the free-hanging and the fully-loaded positions of the cable. The importance of nonlinear geometric effects may be appreciated from this figure and the values of cable displacement.

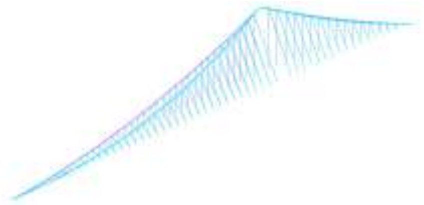

Figure 14. Cable deflection

Load Transfer Monitoring

The key issue for the erection of the SAS was the load transfer of the box girders from the temporary trusses to the cable system. This took place after the box girder had been assembled on the trusses, the main cable was erected and compacted, the cable bands bolted in place, and the hangers hung from the cable. The load transfer was accomplished by progressive jacking of the hangers until they could be socketed to the box girders (Fig. 15).

Figure 15. Hangars shown during load transfer

The load transfer was accomplished in three main phases, as illustrated in Fig. 16. Only about one-half of the total hangers were installed in Phase 1 (top of Fig. 16), to simplify the construction staging. However at this stage of erection approximately 90% of the weight of the box girder (less paving, utilities and bikepath) has been lifted by the main cable and the Phase 1 hangers. It is clear that the erection forces in these hangers are on average 90% higher occurring during the service life of the bridge (25% of the breaking load), which is acceptable temporarily. Great care was taken with the exact sequencing of the Phase 1 hangers, in order to avoid overstressing them by an uneven distribution of load between individual hangers. Phase 1 was divided into about 50 steps and throughout the load transfer the jack pressures and the remaining length to be jacked was monitored, in order to control interim hanger tensions. Note that in Phase 1 three hangers at the tower remained uninstalled. These were placed in Phase 2 (center of Fig. 16).

Phase 2 included just the three main span hanger positions adjacent to the tower, and this phase was introduced to control cable bending, as described in the next section. The timing of the Phase 2 hanger erection had an effect on the overall lift-off of the bridge from the falsework. The deflection of the box girder at the end of Phase 1 of hanger erection is shown in Fig. 17. It may be seen that the box girder has lifted off of the temporary truss over most of its length, but remains in contact with one cradle near the tower and with one cradle near the East Pier. The two last supporting cradles needed to be checked for interim wind and seismic loadings for the period of time between Phase 1 and Phase 2. This effort was justified by the need to mitigate cable bending, as described below.

Phase 3 of load transfer (bottom of Fig. 16) completed the installation of the hangers brought the suspension system to near its final position.

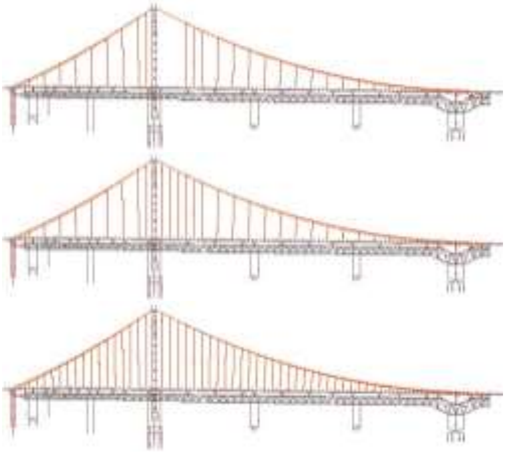

Figure 16. Three phases of load transfer via hanger installation

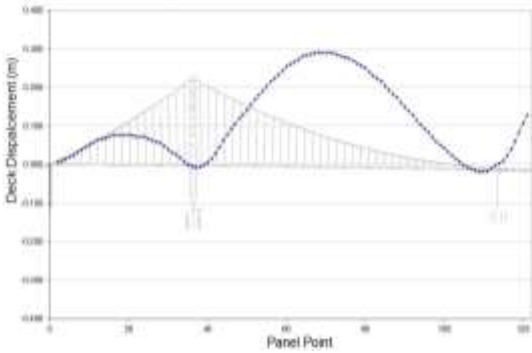

Figure 17. Deflection of box girder after phase 1 of load transfer

Cable Bending

One normally thinks of the main cables of suspension bridges as carrying tensile forces; and this is their primary behavior. But cables may also carry bending moments. The issue of cable bending is complex. Bending moments may arise in a cable through the interaction of three factors: Rotation of the cable due to large displacements in space; The tension in the cable; The lengths of cable bands, which impart flexural and shear rigidity to a portion of the cable; The spacing of the cable bands.

The cable bands rotate with the cable as it swings out and down from the FHC position. Rotation of the cable bands generates force couples due to the tension in the cable acting through the relative displacements of the ends of the cable bands. These couples are equilibrated by bending moments in the cable.

For the SAS, this issue was studied using the ADINA model shown in Fig. 14. The cable modeling included all the individual PWS strands (the cable was pre-fabricated in 137 strands) to form the cross-section of the cable. The model also includes the cable bands to their actual lengths, matching the actual cable bands in sufficient detail to compute the bending moments and rotations in the main cable arising from the phenomenon described above.

This analysis indicated that load transfer could potentially generate unacceptably high bending stresses in the cable in the main span near the tower. This section of the cable is restrained from rotating by the tower saddle (which is fabricated to the final geometry) and so attracts bending stress resulting from the cable movements. These stresses were avoided by delaying the installation of three hangers at the tower, and the tightening of their cable band bolts. Without these bands installed, the cable was provided a 35 m length that was very flexible. As a result, the large displacements of phase 1 were accommodated while generating less stress. Phase 2 consisted of installing these 3 hangers.

Cable Twist

Related to the phenomenon of cable bending is cable twist. As the cable was displaced from its free-hanging to its fully loaded position, it twisted about its own axis, as was observed earlier in the Youngjong Bridge. The problem was solved by accurate predictions of cable twist, and the specification of compensating camber in the cable band installation. The ADINA model shown in Fig. 14 was used to study the twist of the cable and to compute a twist camber to be applied to the cable bands before load transfer.

Cable Band Installation Angles

The computed rotations of the main span cable bands are shown in Fig. 18—this is labeled "structural response" in the figure. The curve labeled "total rotation" is the intended final inclination of the cable bands to match the hanger angles between the cable and the edge of the box girder (see Fig. 15 and Fig. 14). The difference between these is called the "cable band camber". The cable bands were placed on the cable in a rotated position in accordance with this camber (see Fig. 19). The camber varies from about 20 degrees near the tower and anchorage (where the cable rotates little) to about 5 degrees at midspan (where the cable rotates a lot). It may be observed in Fig. 18 that the rotation of the cable even reverses direction near the tower.

The as-built measurements of the completed cable after load transfer demonstrated the success of the construction analysis and the use of cable band camber. Only two cable bands deviated from the analyzed value by more than 1.5 degrees, and these cases may possibly be attributed to installation error.

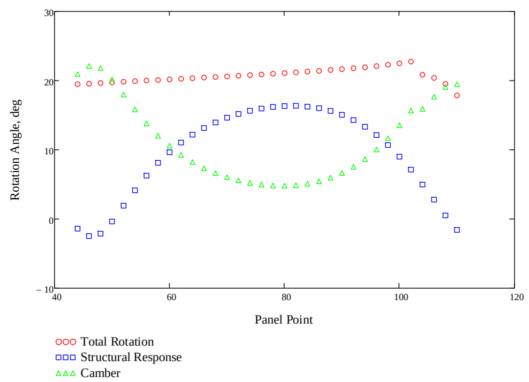

Figure 18. Cable twist and camber

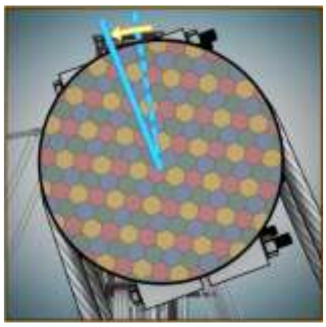

Figure 19. Cable band rotation during load transfer.

Conclusion

The fabrication and construction of the self-anchored suspension bridge has been a challenging undertaking. It has required specialized analysis, and extensive monitoring of tolerances and geometry throughout the work. Furthermore, it has required the investigation of issues not often encountered in bridge erection, like cable bending and cable twist. The detailed modeling served to:

- Verify the on-going construction quality
- Address deviations in expected behavior during construction
- Confirm the serviceability of the final structure