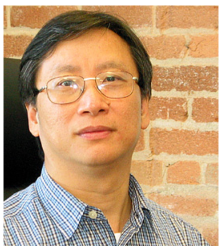
CONSTRUCTION ENGINEERING FOR THE HONG KONG-SHENZHEN CABLE-STAYED BRIDGE



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BIOGRAPHIES

Dennis Jang is Vice-President, Project Director at T. Y. Lin International. Mr. Jang is currently the Project Manager for the Shenzhen Western Corridor Bridge Project and for the San Francisco-Oakland Bay Bridge Project. He has also managed the following cable-stayed bridge projects: the Cooper River Bridge in South Carolina, the Sidney Lanier Cable-Stayed Bridge in Georgia, the Seohae Grand Bridge in Korea and the My Thuan Bridge in Vietnam.

Ms. Mibelli is a Bridge Engineer at T.Y.Lin International. For the Shenzhen Western Corridor she provided erection stage analysis; stay cable stressing sequence; and detailed erection manual. She performed dynamic analyses of the Self-Anchored Suspension Bridge in the San Francisco Bay and design review for the Cooper River Bridge and the Indian River Arch Bridge in Delaware.

Austin Pan is a Senior Bridge Engineer at T.Y.Lin International. Dr. Pan has performed design and construction reviews, and erection engineering for long-span bridge projects, including Shenzhen Western Corridor, the Cooper River Bridge, the Benicia-Martinez Bridge in California, and the cable-stayed Nanjing Third Bridge in China. He also has teaching and research experience at Purdue University.

Mark Chen is a Senior Bridge Engineer at T.Y.Lin International. Mr. Chen has provided erection engineering services for Shenzhen Western Corridor, Cooper River Bridge, and Seohae Grand Bridge; stage analysis for the Weirton-Steubenville Bridge in Ohio and West Virginia, and served as Project Engineer for the construction of the Sun Yat-Sen Freeway in Taiwan.

SUMMARY

The Shenzhen Western Corridor is a 5.1-kilometer long expressway that links the cities of Hong Kong and Shenzhen, China. The expressway includes two cable-stayed bridges with single towers inclined towards each other. The cable-stayed bridge on the Hong Kong side, has a main span of 210 m and a back span of 99-m. There are also two 74.585-m side spans that are preceding and structurally continuous with the cable stay back span.

This paper presents details of the construction engineering services performed by T.Y. Lin International during the tender phase and the construction phase for the cable-stayed bridge. The construction bridge began in July 2004 and is scheduled to be complete near the end of 2005.

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INTRODUCTION

The Shenzhen Western Corridor is a 5.1-kilometer long dual three-lane expressway that spans Deep Bay, linking the cities of Hong Kong and Shenzhen, China. The focal point of the project are two cable-stayed bridges with towers inclined towards each other, symbolizing the relationship between the two united regions. The construction of the 3.2-km section on the Hong Kong side, including one of the two cable-stayed bridges, was awarded to the Gammon – Skanska -MBEC Joint Venture (CSM-JV). The design of the 460-m long cable-stayed bridge features a configuration that combines a single-pylon tower and a single plane of stay cables. The 210-m main span is anchored by a 99-m back span that is structurally continuous with two more 75-m back spans. The bridge deck is an aerodynamically shaped steel orthotropic box girder, 38-m wide and 3.9-m deep. The single-pylon concrete tower inclines at a 1 to 5 ratio for a height of 152-m. The back span pier is anchored by tie-downs and counterweights in the box girder. Tuned mass dampers will be installed in the main span to control wind-induced vibrations.

This paper presents details of the construction engineering services performed by T.Y. Lin International (TYLI) for the CSM-JV during the tender phase and the construction phase for the Shenzhen West Corridor cable-stayed bridge. The original tender document had envisaged the use of extensive temporary falsework and foundation work over the environmentally sensitive waterway. The winning tender that the CSM-JV submitted entailed an alternative construction scheme that is fast track, economical, and environmentally friendly.

All of the intermediate temporary back span supports in the waterway were eliminated and the CSM-JV and TYLI employed a scheme of heavy lifting the back spans as full-length units. The three back span girder supports are first positioned high with temporary shims of specifically calculated thicknesses. As the back spans are joined together and made continuous, their supports at the piers are lowered in a predefined sequence by removing the shims. In this manner, girder internal forces can be controlled and the moment diagram specified by the Design Engineer is closely matched.

The erection of the 210-m main span is by the cantilever segmental construction method. The main span steel deck segment erection begins prior to finishing the concrete tower. This is not only to save construction time; it also helps achieve tower concrete crack/stress control. The stay cable forces from the main span deck weight will reduce the tensile bending stress in the tower caused by its eccentric dead weight due to its 1 to 5 inclination.

A 120-ton lifter is used to lift the 250-ton main span segments from the barge. The orthotropic steel box segments are joined together by field welding. The typical erection cycle time for a segment is 6 working days. Extensive computer analyses were performed to ensure geometry control and structural safety at each stage of construction as well as to facilitate construction.

Safety of the bridge under wind and seismic loading during construction was also assessed. The Hong Kong area is subject to high wind demands during the typhoon season and wind loading governed the lateral design of the bridge during construction; however, wind studies concluded that the fully extended cantilever bridge during construction is aerodynamically stable and that temporary wind tie-downs were not required. Temporary tower wind fairings were added to assure wind stability during construction. The construction of the cable-stayed bridge began in July 2004 and is scheduled to complete near the end of 2005.

BRIDGE DESCRIPTION

The Shenzhen Western Corridor is a dual three-lane expressway that will span the Deep Bay, linking Ngau Hom Shek in Hong Kong with Shekou in Shenzhen. The construction of the 3.2-km section on the Hong Kong side was awarded to the Gammon-Skanska-MBEC Joint Venture (JV); the remaining 1.8 km will be built by the Shenzhen government. The focal point of the Shenzhen Western Corridor will be the two single tower cable-stayed bridges, with towers inclined towards each other.

The JV's responsibilities include the cable-stayed bridge in the Hong Kong side, which has a main span of 210 m and a back span of 99-m. There are also two 74.585-m spans that are preceding and structurally continuous with the cable stay back span.

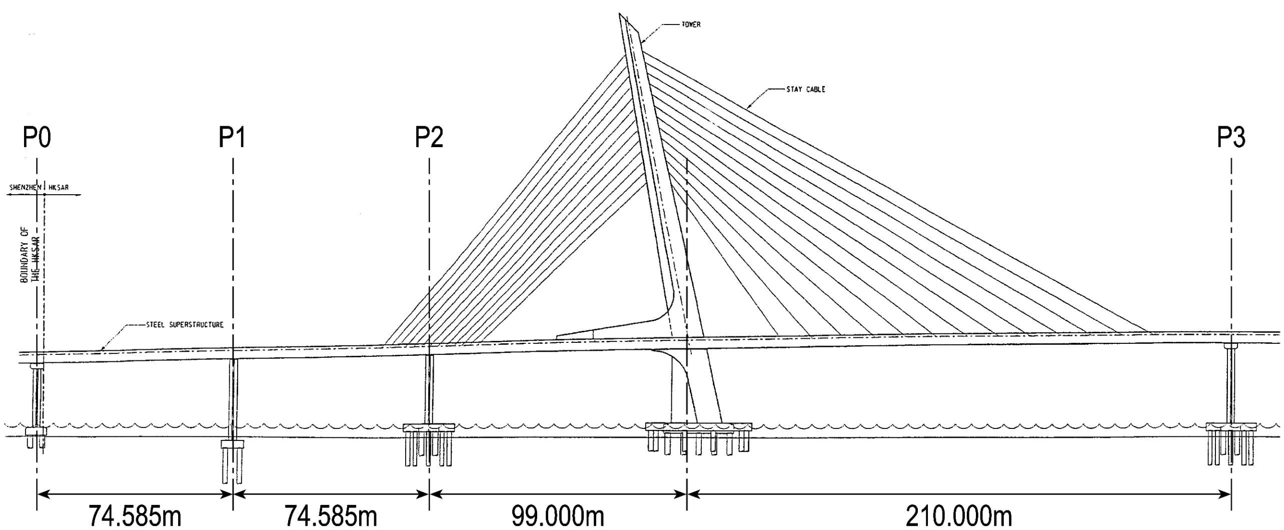


Figure 1: Cable-Stayed Bridge Layout

The bridge tower and piers are of reinforced concrete construction. The 152-m hollow tower with rectangular cross section of varying dimensions has an inclination ratio of 1:5. The bridge superstructure is steel orthotropic box girder construction. The deck, which is 37-m above the water, is 37.6-m wide and 3.9-m deep.

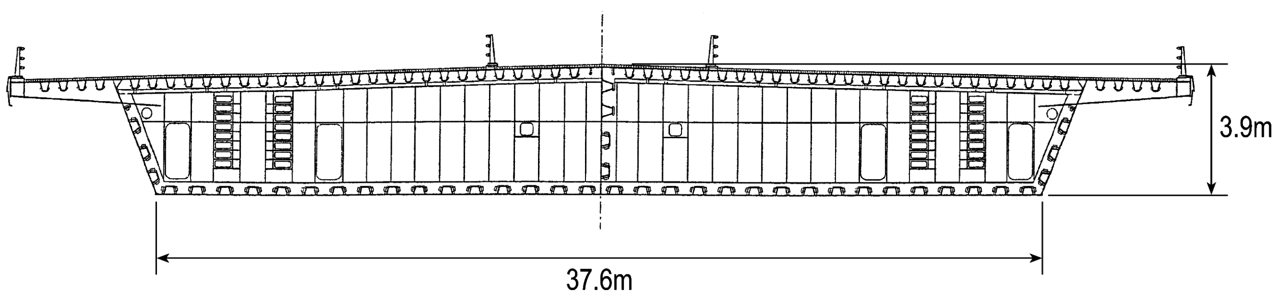


Figure 2: Steel Orthotropic Box Girder

The 13 pairs of stay cables are configured on a single plane. Thirteen stays support the main span and thirteen stays, anchored in the back span pier, balance the large moments caused by the main span weight on the tower. The inclination of the tower also helps to balance the tower moments. Freyssinet's stay cable system was selected for the project. The system consists of 15mm diameter, high tensile 7-wire galvanized steel strands sheathed with a high-density polyethylene (HDPE) coating. The number of strands per cable in the project varies from 29 to 95. Dampers will be provided to control cable vibrations such that 4% log decrement damping is achieved. In order to achieve project specifications the stressing sequence calls for initial stressing during main span cantilever erection and final cable adjustment after closure. Freyssinet is provided with both the cable displacement (elongation or relaxation of cable) and expected target force for each stay cable stressing and adjustment operation.

Counterweights and steel tie-downs will be placed over the anchor pier to avoid the uplift caused by the back span stay-cables. Tuned mass dampers will be installed inside the box girder in the completed bridge to control wind-induced vibrations.

CONSTRUCTION ENGINEERING

T.Y. Lin International performed construction engineering for the Shenzhen Western Corridor Cable Stayed Bridge. The construction engineering for the project faced challenges from both stringent specifications requirements and tight schedule:

The bridge location, Deep Bay, which is a shallow estuary, is an environmentally sensitive area. Reducing the environmental impact to the bay and protecting the local oyster cultivations was a high priority when planning the bridge construction method.

The project required tight tolerances in the geometry of both the superstructure and tower. The required construction tolerance for the superstructure in the longitudinal direction is L/2000, where L is the span length between centerline of piers. In the transverse direction, the tolerance is Lt/1000, where Lt is the transverse distance between the bridge centerline and edge of the deck. These requirements are about twice as stringent as those in typical construction. It is important to achieve a smooth curve for the final bridge profile so as not to impair rideability. The recommended tolerance for the tower is H/1000 in both lateral and vertical directions, where H is the vertical tower height. The inclined tower required additional attention to geometry and stress control. As the crack concrete modulus is difficult to control and estimate, the erection sequence is planned such that the tower concrete is always under compression during construction. This is accomplished by erecting the main span steel deck and the concrete tower anchorage zone segments concurrently. In addition, the time dependent effects due to concrete creep and shrinkage are accounted for in tower camber calculation.

In order to make the very demanding construction schedule, continuous efforts are made by the Contractor and Construction Engineer to streamline and simplify erection procedures, especially for critical-path activities. Some of the examples include:

1. Eliminate the temporary falsework and its foundation below deck to support the tower crane, which climbs full height alongside the tower. This allows tower construction to progress without being slowed down by the availability of the tower crane. Through detailed finite element analyses of the superstructure deck under various tower crane loads, the Contractor was able to remove the false work below deck. To distribute the crane loads, temporary spreader beams were used to span across three deck diaphragms at the crane base connection. The permanent structure is not overstressed at any time during construction, as the maximum crane load reaction is smaller than the future superimposed dead load plus live load in the distributed area.
2. Allow partial field welding in the steel deck segment splice joints before stressing the cables to cut down the typical cycle time of the superstructure main span to 6 days. All splice welds for the box section perimeter as well as for the interior webs are done first. Before initial stressing of stay cables, at least 50% of the splice welds in the longitudinal ribs are complete. The weld sequence for the infill troughs generally follows the stay cable force distribution, taking into account the shear lag effect in the leading segment. Temporary post-tensioning is employed to provide preload (clamping force) across the joint in order to maintain structure stiffness during stay cable stressing (i.e. to avoid “kinks” at the joint). Analyses performed have confirmed that the locked-in stresses due to the welding sequence are negligible.

The project specifications require the construction engineer to demonstrate that stress levels in all bridge elements are within allowable limits at every stage of the construction. Geometry control data for each erection stage needs to be submitted before construction begins. At the completion of bridge construction, the bridge geometry and member forces under dead load have to be within the specified ranges. In particular, the completed bridge must closely match the Designer Engineer's Reference Moment Distribution along the box girder and the tower, Reference Cable Forces, and geometrical alignment.

The project design criteria are very stringent with respect to stability of the bridge under wind during construction. The specifications require that the bridge during the construction period be able to resist winds of up to187 mph (as high as the design wind used for the design during the life of the bridge). TYLI's wind consultant, West Wind Laboratory (WWL) in Monterey, California constructed 1:40 scale sectional models for the tower and superstructure and performed wind tunnel tests. Numerical analyses were performed with the parameters obtained from the wind tunnel tests to simulate various construction stages and the completed bridge.

The construction engineering also included determination of fabrication and erection cambers; determination of cable stressing sequences and cable lengths; assisting the contractor in the assurance of quality, safety, and environmental standards; recommending measures for reducing and managing risk during construction; and assisting the contractor in accomplishing the above objectives within the contract allowed schedule and budget.

Originally Envisaged Construction Scheme

The construction scheme in the tender document entailed the use of extensive temporary falsework and temporary piles, as denoted by the red circles in the sketch below. This construction scheme was replaced by a scheme involving heavy lifting of the back spans as full-length units avoiding the need for the temporary towers at back span. Improved protection of the waterway was a direct consequence of the elimination of the temporary works.

The general phases of the originally envisaged erection scheme are illustrated below:

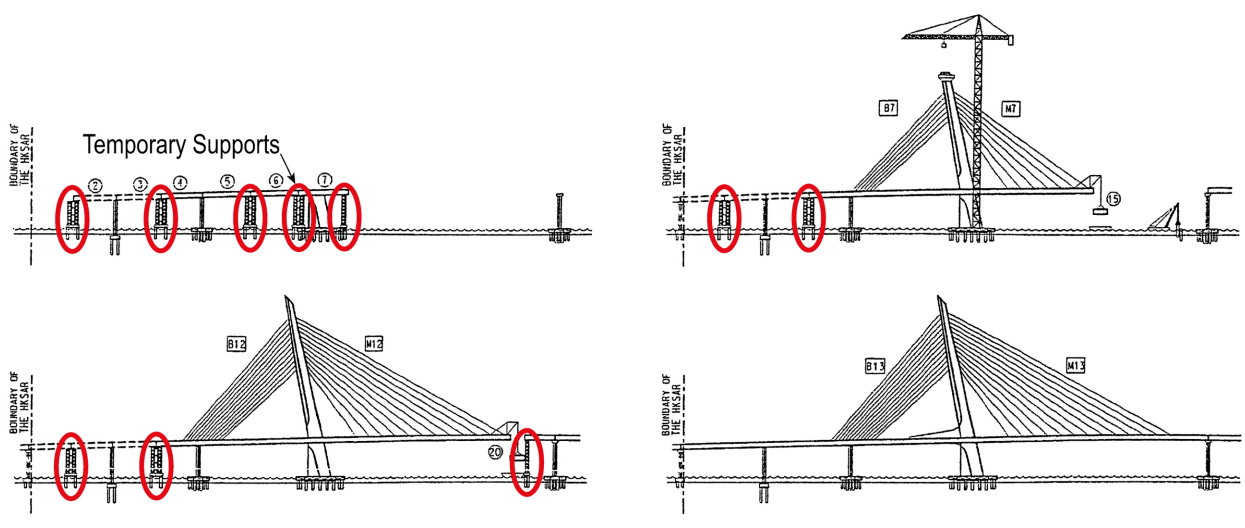


Figure 3: Erection of back span in half-length units, simply supported on permanent piers and temporary towers. After they are connected and made continuous, the temporary support towers are removed; Erection of typical segments concurrently with the tower; Erection of last bridge segment (closure); Bridge completion.

Proposed Erection Scheme

The main superstructure erection scheme consists of erecting each of the back spans in one piece The tower is erected simultaneously up to a couple of segments above the first cable anchor segment and then the main span segmental construction progresses in parallel with the erection of the rest of the tower segments until tower completion and Main Span closure.

As previously mentioned, this scheme is fundamentally different from the designer's scheme in the fact that there is no need to use temporary towers in the middle of each back span and at the closure segment consequently avoiding the need to drive temporary piles.

To compensate for this, the back span girder supports are first positioned high with temporary shims of specifically calculated thicknesses. Then as the three back spans are joined together and made continuous, their supports at the piers are lowered in stages by removing the shims.

It is important to note that different erection sequences cause different locked-in stresses in the structure. The designer had avoided large self-weight moments at mid-span by temporary supporting the span at those locations. Following a different erection sequence without any adjustments, such as shimming, would have led to a different dead load state than the one intended by the designer and overstressing of the girder could have happened. By following the back span lowering sequence the girder internal forces can be controlled and the moment diagram specified by the Design Engineer can be closely matched.

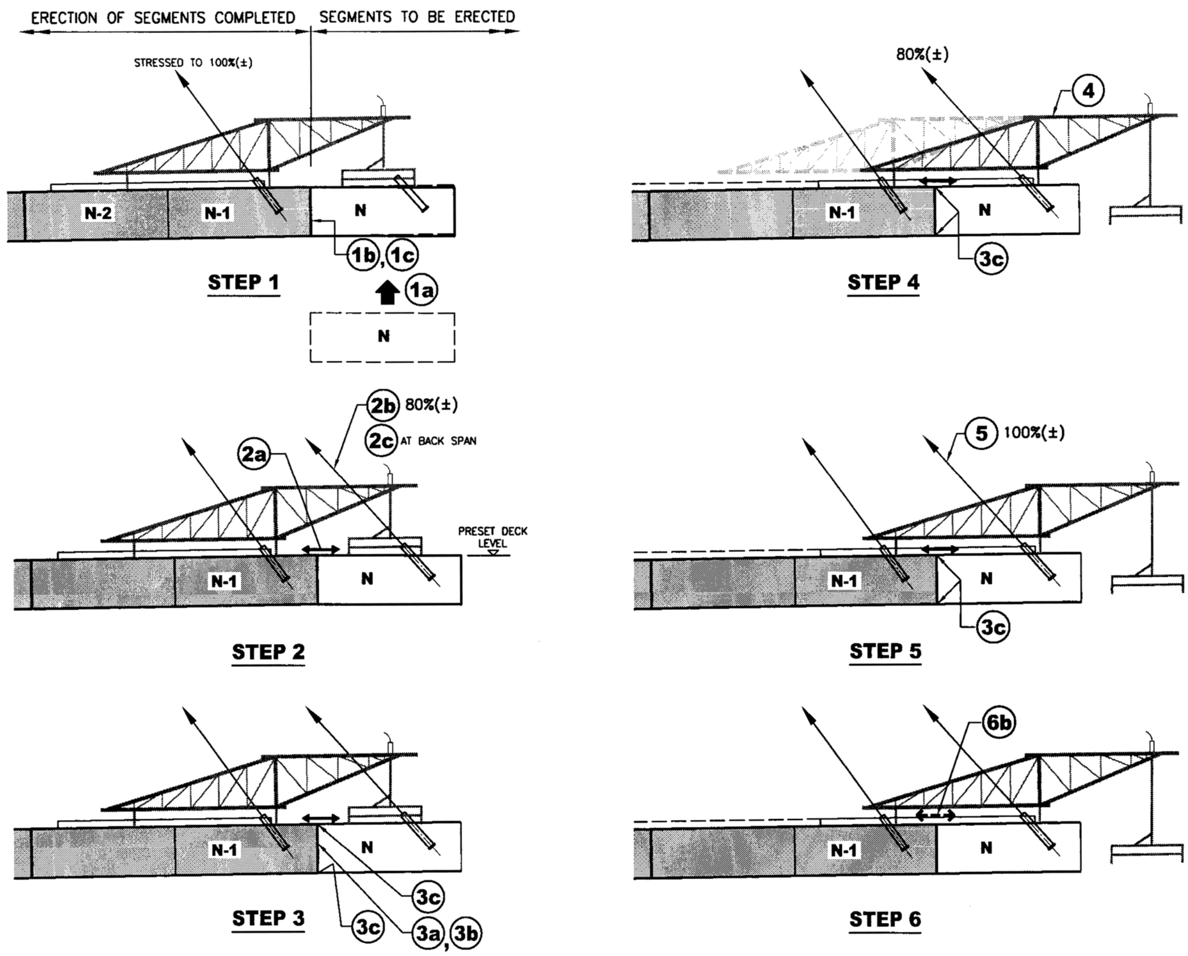
In addition to the temporary towers at the middle of back spans, the temporary tower for the main span closure segment was also eliminated. A lifting mast will be constructed on the viaduct pier, in lieu of additional temporary pier support, foundation, and piling. The alternative construction method requires no change to the Engineer's original design and cross sections. It eliminates the environmental impact as well as ship collision hazard by deleting temporary supports in the waterway; it also improves the quality of the back span structures by removing field welding at the critical mid span locations.

The WWL study results corroborated Designer's wind reports that the fully extended cantilever superstructure deck during construction is aerodynamically stable and consequently the temporary wind tie-downs or other wind countermeasures for the cable-stayed bridge during construction are not required. Wind fairings were added to the top 1/3 height of the tower to assure tower wind stability during erection.

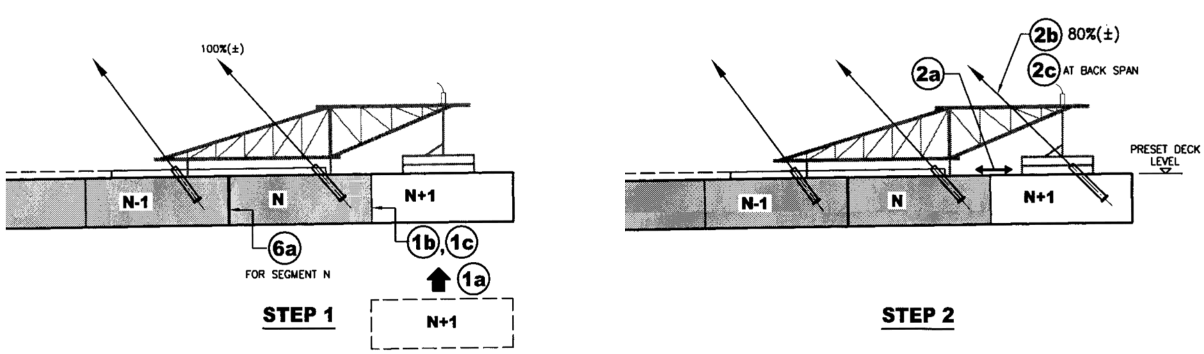
The major details of the proposed erection scheme are:

- Construction of foundations, pairs of piers (P0, P1, P2 & P3), tower below deck, pier tables. Installation of temporary supports, shims, and lifting jacks.
- Start erection of tower above deck.
- Lift and weld prefabricated segment Back Span 2 between P1 and P2. Lift and weld prefabricated segment Back Span 3 between P2 and P3.
- Jack and remove shims of 520mm and 78mm at P1 and P2 respectively.
- Lift and weld prefabricated segment Back Span 1 between P0 and P1.
- Jack and remove shims at P0, lowering the deck by 140mm.
- Install counterweights at P2 piers.
- After a couple of cable anchor zone segments of the tower have been constructed, start Main Span erection. TYLI worked closely with the contractor Gammon Construction to analyze various erection alternates for main span segments to minimize the cycle time. The construction cycle of each typical main span segment is as follows (see also the following sketches for typical main-span erection):
    - Lift, position and weld girder segment.
    - Install and stress stay cable on main span side. Install and stress corresponding stay cable on back span side.
    - Erect one tower segment
    - Advance lifters.
- Stress tie-downs at P2
- Set up lifting mast over viaduct Piers P3. Erect closure segments. Install counterweights.
- Final adjust all stay cables.
- Install barriers, overlay, etc. Activate tuned mass dampers.

ERECTION OF SEGMENT N



ERECTION OF SEGMENT N+1



STEPS 3 TO 6 SIMILAR TO SEGMENT N

Typical Main Span Segment Erection Sequence

1a – Lift Segment N from barge
1b – Complete welds for box perimeter and central web of box section
1c – Test welds
2a – Apply preload to deck plate
2b – Install and stress Main Span Cable M (1st stage to about 80%)
2c – Install and stress Back Span Cable B (one stage to 100%)
3a, 3b, 3c – Weld infill troughs
4 – Launch lifters and fix them at new positions
5 – Stress Main Span Cable M to 100% (2nd stage)
6a – Complete test and remedial works as required
6b – Release temporary preload to deck plate (prior to lifting Segment N+1)

ERECTION SEQUENCE ANALYSIS

The software TANGO was the main tool used to develop the proposed erection scheme and in performing the stage-by-stage construction analysis. This program was developed specifically for bridge construction; therefore, features such as consideration of all locked-in stresses during construction; creep, shrinkage and other time dependent effects; changes in cable stiffness based on actual forces; and operations with internal forces and deformations are built into the program.

At each stage of construction, the program calculates displacements and rotations, girder stresses and internal forces, as well as cable forces. The required first stage cable stressing was determined through an iterative procedure in order to match the final moment distribution specified by the designer. For the jacking of the three back spans, a system of simultaneous equations were derived and solved to determine the jacking heights required to achieve the target moment distribution.

Erection Sequence Analysis Results

The following series of Back Span moment diagram plots (Plot A thru Plot H) at critical construction stages illustrate how the designer's Reference Moment Diagram is achieved using an erection scheme different from the one originally envisioned by the designer. In order to control construction stresses and to achieve the Designer's Reference Moment Distribution for the three back spans, the bridge girders will be lifted and placed at a higher elevation on temporary shims with heights specifically calculated:

- Pier 1 Shims = 520 mm
- Pier 2 Shims = 78 mm
- Pier 0 Shims = 140 mm

After the backs spans are welded and made structurally continuous with the rest of the bridge, the shims are removed. As the shims are removed and girders are lowered, bending is induced in the spans, so that the final superposition of moment diagrams will closely match the Designer's Reference Moment Distribution.

<u>Plot A</u>
When the full Back Spans 2 and 3 are first lifted in place their moment diagrams correspond to the ones of simply supported beams. The bridge girders are placed at higher elevations over Piers 1 and 2 with temporary shims.

<u>Plot B</u>
Back Spans 2 and 3 have been welded to the pier table segments. The two back spans now form a continuous structural system. The 520-mm temporary shims on Pier 1 are then removed. The lowering of the bridge girder at Pier 1 induces a moment diagram into the system, as shown by this plot.

<u>Plot C</u>
The 78-mm temporary shims on Pier 2 are removed. The lowering of the bridge girder at Pier 2 induces a moment diagram into the system, as shown by this plot.

Plot D
This plot shows the resultant moment diagram from the superposition of Plots A, B and C. Comparing Plot D with Plot A, note that there is now a reduction in positive moment (tension in bottom plate) in the system. The amount of this reduction is dependent on the shim height selected.

Plot E
Span 1 is lifted in place. Similarly, it starts out with the moment diagram of a simply supported beam.

Plot F
Span 1 is welded to the rest of the bridge. The 140-mm shims over Pier 0 are removed. The moment diagram induced into the continuous system is shown.

Plot G
Superposition of Plots E and F results in the moment diagram at the completion of back span construction.

Plot H
To the completion of the whole bridge, the back span moment diagram is further adjusted by other actions including the installation of back span stays, added counterweight, superimposed loads such as overlay, etc. Note that the final moment diagram that will be achieved closely matches the Designer's Reference Moment Diagram.

Moment Diagram units are KN-m/10.

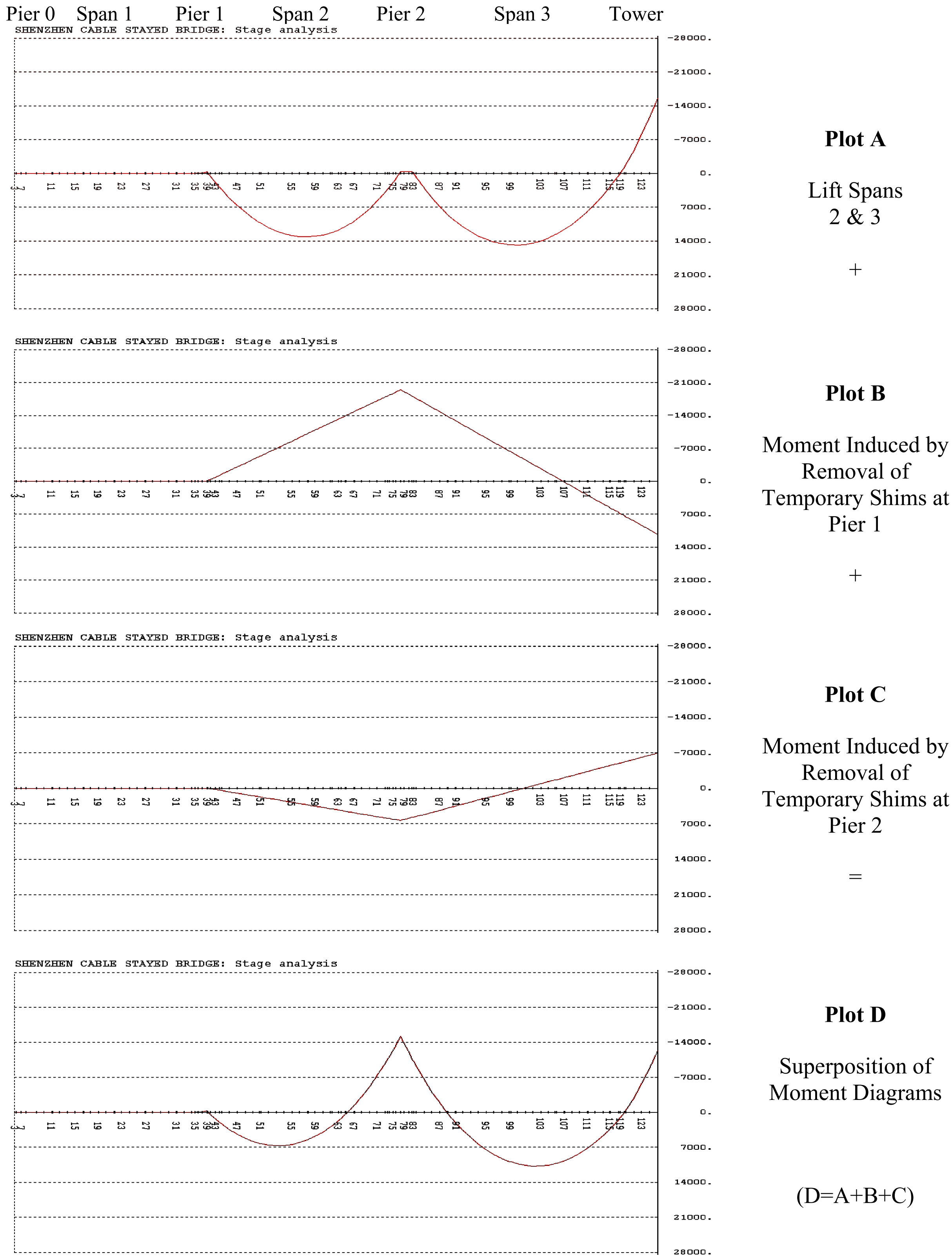


Figure 4: Back Span Moment Diagram at Critical Construction Stages

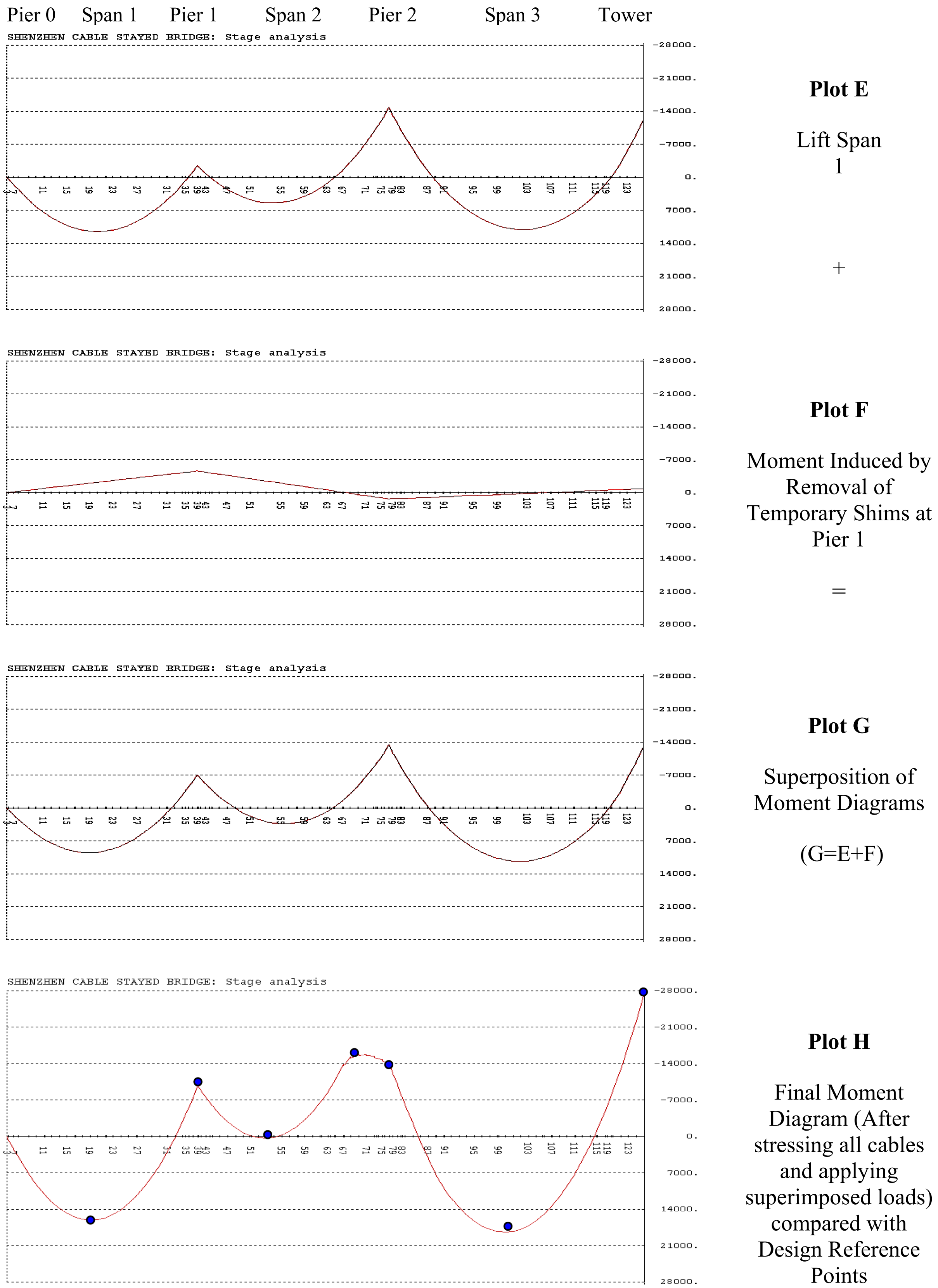


Figure 4 (cont): Back Span Moment Diagram at Critical Construction Stages

The following plot shows a comparison of box girder moment diagram in the cases in which shims are used to control the final moment diagram vs. the moment diagram that would have resulted if the shims were not used. The main span moment was adjusted by controlling the initial cable stay stressing and final cable adjustments. Note that Designer's cable forces were also matched within 5% of specified reference values, consequently moment diagram in the cantilevering tower also matches designer's moment diagram.

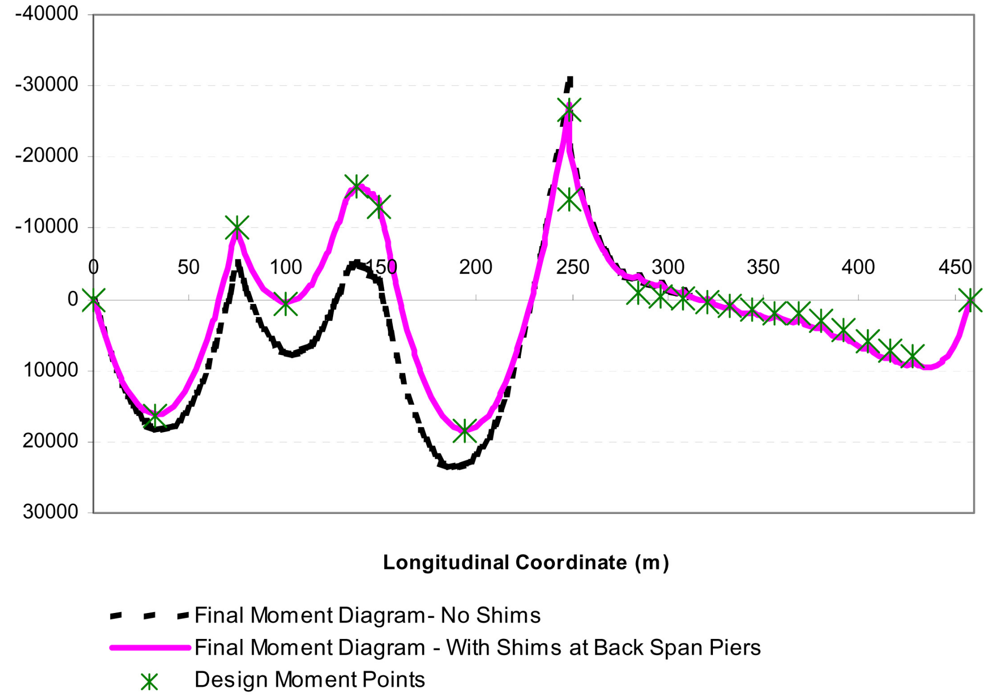


Figure 5: Final Box Girder Moment Diagram (KN-m/10)

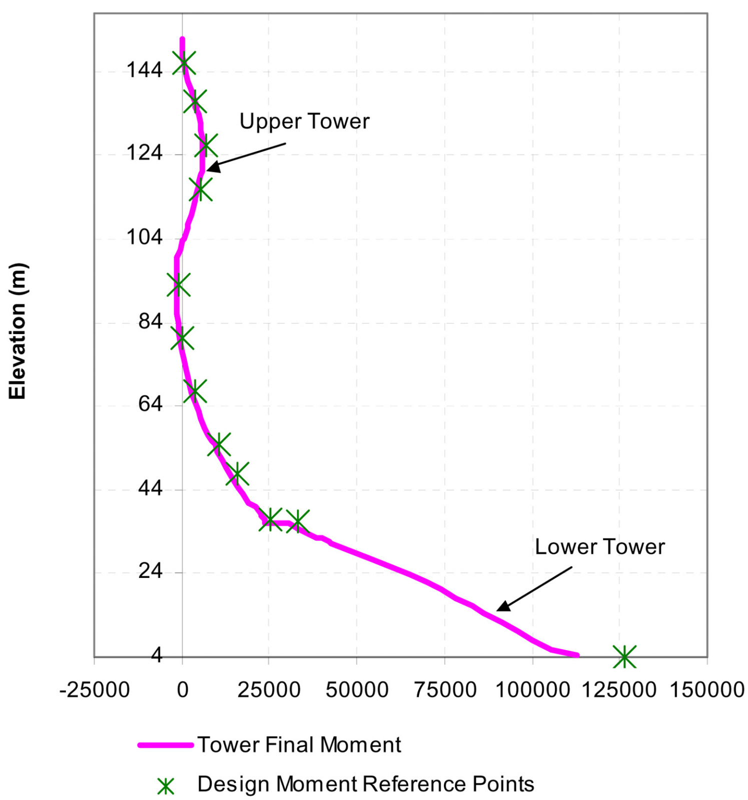


Figure 6: Tower Moment Diagram (KN-m/10)

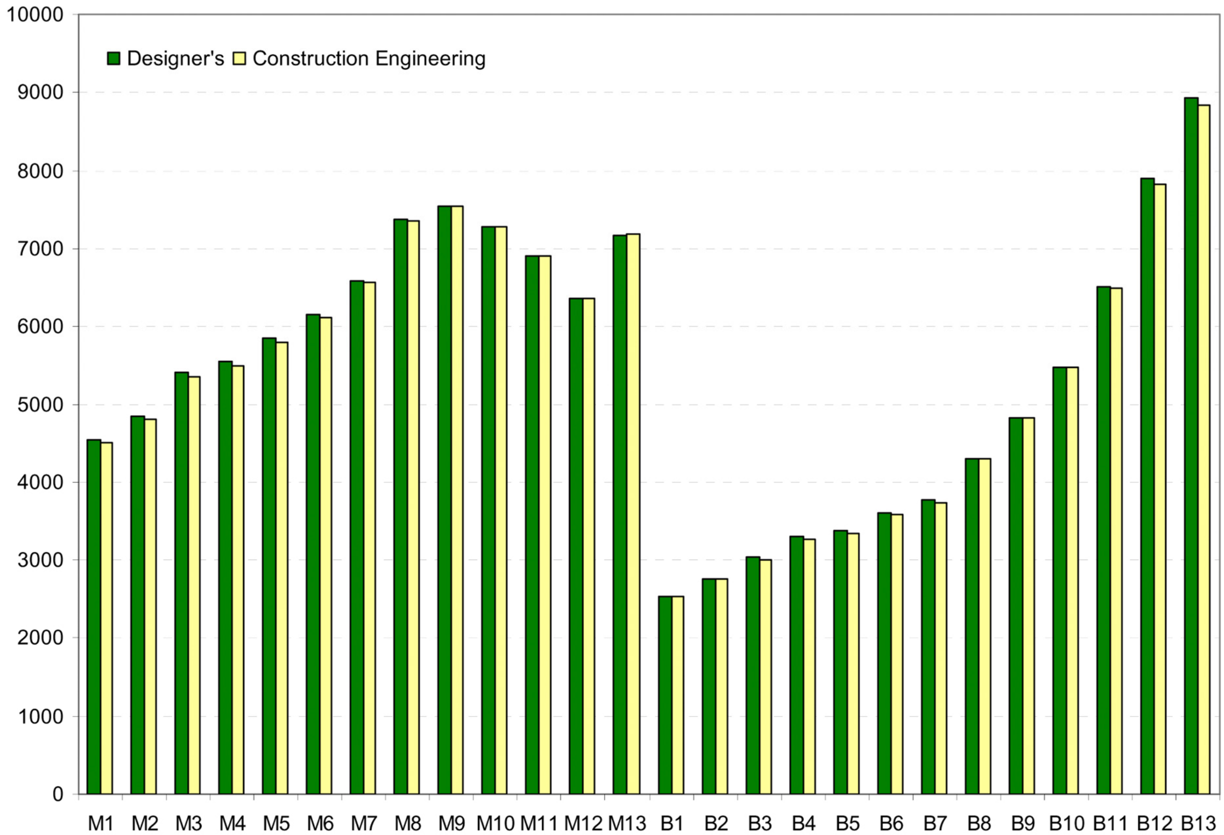


Figure 7: Final Cable Forces (KN)

CONSTRUCTION UPDATE

At the time of finalizing this paper in September 2005, three back spans of the cable-stayed bridge have been erected (see Figure 8 for back span erection). The erection process entails using strand jacks to lift the segments weighing 1,400 tons and 1,850 tons, field-welding the splice joint on one end and then sliding the segment horizontally by 10 cm to weld the splice on the other end. The main span cable-stayed segment erection began in June 2005. At that time, backspan and main span construction operations were running concurrently. The erection of the first two main span segments took place in the same time period as the lifting of the first back span and the installation of the counterweights over Pier 2. Tower construction was completed in September 2005 (see Figure 9 for tower erection). It is estimated that the main span closure will be done at the end of September 2005 (See Figure 10) and the entire bridge construction will be complete by the end of 2005.

Figure 8: Lifting of Back Span

Figure 9: Progress of Construction as of May 2005

Figure 10: Lifting of the Main Span Closure Segment

ACKNOWLEDGMENTS

Dr. Man-Chung Tang, Technical Director of TYLI, provided the initial concept of the alternative construction scheme as well as technical guidance of the full project. Dr. Jon Raggett provided wind consultation. Dr. Austin Pan is the TYLI Site Engineer and is responsible for the cable-stayed bridge erection analyses and field engineering support.