The New Tacoma Narrows Suspension Bridge, a Continuous Mile of Suspended Steel

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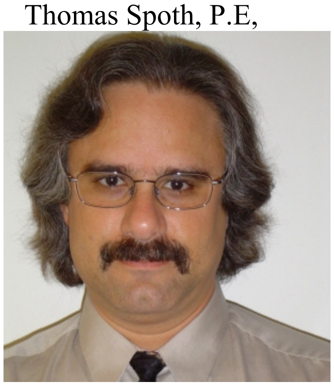

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Biography

Mr. Spoth is Vice President and Deputy Chief Bridge Engineer for Parsons' New York office. He has over 20 years of experience in suspension bridge design and rehabilitation and served as Bridge Design Manager for the subject project and the new Al Zampa Memorial Bridge across the Carquinez Straits in California. He has also performed design and/or inspection on over 25 suspension bridges in the United States and abroad, including Golden Gate, Brooklyn, Verrazano Narrows, and Macinac Bridges.

Mr. Viola is a Project Manager with Parsons with over 20 years of bridge and tunnel design and inspection experience. He served as Superstructure Design Manager and Engineer-of-Record for the subject project and currently also serves as Engineer-of-Record for the Mt. Hope Bridge in Rhode Island. Mr. Viola has also worked on the rehabilitation, design and/or inspection on over 20 suspension bridges. Mr. Viola also serves as President of the ASCE Met Section and Director for ACE Mentoring.

Mr. Condell has seven years of experience in suspension bridge design, rehabilitation and inspection. He served as the Suspended Superstructure Lead for the Tacoma Narrows project. He also served on the design team for the Al Zampa Memorial Bridge and construction engineering team for the Lions Gate Bridge reconstruction.

Summary

The suspended superstructure of the new Tacoma Narrows Suspension Bridge consists of twin welded steel trusses with a continuous and integral orthotropic steel deck measuring over one mile in length. The bridge, including major components of the stiffening truss, was designed to allow for a future lower roadway or light rail transit system. This paper will discuss the design aspects of this 5,400 ft suspended superstructure, including the development of design details to satisfy performance requirements for serviceability, fatigue, wind and seismic. Global superstructure and local component computer modeling techniques are presented as they relate to force, fatigue and displacement demands and overall structural performance for the 150-year design service life. Performance criteria for high seismic hazard and computer analysis techniques using ADINA computer modeling software is described. Wind performance and physical wind tunnel testing utilizing full-bridge aeroelastic models for the bridge in its completed configuration is also presented. The current state of fabrication and lessons learned will also be discussed.

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By

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PROJECT HISTORY AND BACKGROUND

The Tacoma Narrows in Washington State is the narrowest waterway in Puget Sound, separating the Olympic Peninsula from the rest of Washington State. In 1940 the first suspension bridge spanning the waterway opened to traffic. Dubbed "Galloping Gertie," it collapsed a short four months later and still endures as the model of a most graphic and unforgettable engineering failure. Gertie also became a great teaching tool for bridge engineers to improve their knowledge on how to design and build suspension bridges.

In 1950, ten years after Gertie's spectacular collapse, the second Tacoma Narrows Bridge opened to traffic. Built directly on Gertie's foundations, it has since provided a reliable route across the Narrows for decades. However in recent years, increasing traffic demand along State Route 16 has exceeded the highway's and the bridge's four-lane capacity. Motorists living in Kitsap County experience extreme directional peak traffic flow as they travel to Tacoma, Seattle, or other points east of the sound in the morning, and they see the reverse congestion in the evenings. Traffic backups have become commonplace and are key to the Washington State Department of Transportation's (WSDOT) decision to build a parallel suspension bridge to provide needed highway capacity.

On September 25, 2002 WSDOT issued Tacoma Narrows Constructors (TNC), a Joint Venture of Bechtel Corporation and Peter Kiewit and Sons, a Notice to Proceed. The Notice to Proceed allowed TNC to design and construct 2-1/2 miles of improvements to State Route 16, 5400 feet of which is the new parallel suspension bridge. Parsons/HNTB Joint Venture served as the designer for TNC. Nippon Steel / Kawada Bridge (NSKB) were awarded fabrication and erection engineering and elected to supply the steel and subcontract most of the fabrication to Samsung Heavy Industries (SHI).

The new Tacoma Narrows Bridge has a unique orthotropic deck system that is integral with the superstructure stiffening trusses and the design includes provisions for a future lower roadway or light rail system. The project schedule included a fast track design (now complete) to meet the 55-month overall project delivery schedule, ending in April, 2007.

Basic Features

The new Tacoma Narrows Bridge is located about 180 ft south of the existing bridge. The main span is 2,800

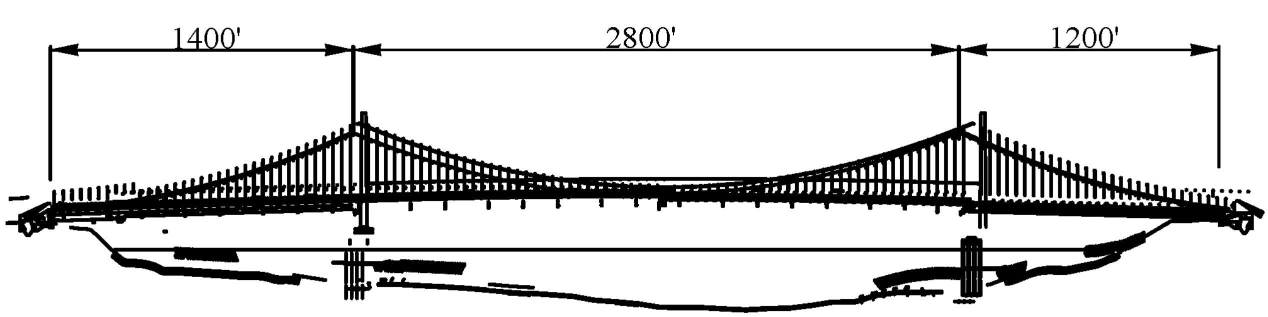

Figure1: General Plan and Elevation

ft with flanking side spans of 1,400 ft and 1,200 ft (see Figure 1). The roadway accommodates three highway lanes, two shoulders and a bicycle-pedestrian path (see Figure 2) but may be expanded to four highway lanes with the bicycle/pedestrian path. The structural system for the suspended superstructure consists of 23'-6" deep trusses with an integral orthotropic deck at the top chords. Supporting the superstructure are two 20½" diameter main cables of high-strength steel wire. The main cables consist of galvanized high-strength 0.196" diameter steel wire, air spun into nineteen (19) strands per cable in a hexagonal pattern, and then compacted. Each strand is to be composed of 464 wires resulting in a total of 8,816 wires per cable. Hollow-shaft reinforced concrete towers top out at elevation 510 (ft) and consist of inclined legs and three cross struts. They bear the load of the main cables and are founded on deep water dredged caissons. Certain components of the bridge, including the towers, stiffening truss chords and diagonals, are also designed to accommodate a

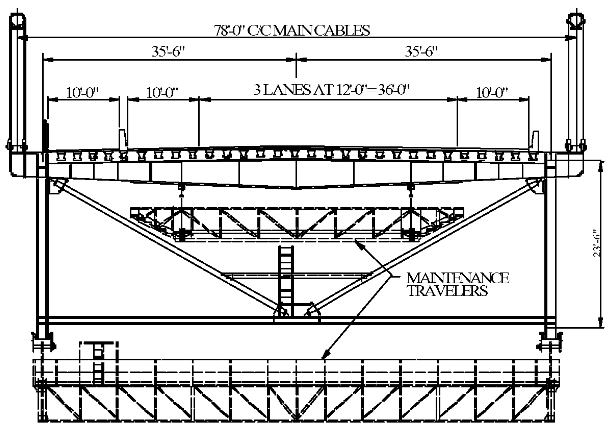

Figure2: Typical Cross Section – Upper Roadway Configuration

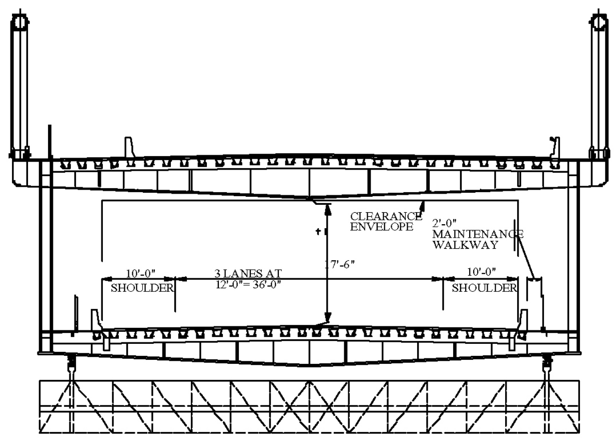

Figure 3: Typical Cross Section – Future Lower Level Configuration

future lower level with three lanes of traffic or light rail transit (see Figure 3).

The design of the bridge has incorporated the following design features:

- Tapered floorbeams
- 20 ft span, fatigue resistant trapezoidal orthotropic deck ribs that minimize the number of floorbeams and optimize the truss configuration
- High strength steel (HPS 70W) in the orthotropic deck and truss in high stress locations
- Truss bottom chord designed and detailed to act as the maintenance traveler rail
- Truss verticals at even panel points only for the upper roadway configuration
- Innovative main cable strand anchoring system
- Segmental center tie design
- Maintenance access walkways incorporated directly onto the truss lower lateral system
- Outboard rocker link supports at towers to allow the use of two (one upper and one lower) maintenance travelers (in lieu of three each) for the entire bridge.
- Narrow cable splay in the anchorages to minimize the anchorage size, mass concrete, excavation and excavation tie-back systems.
- Sand-filled chambers in the anchorages to reduce the quantity of mass concrete

To better evaluate wind effects and to serve as an independent check of the section models, full-bridge aeroelastic models were designed and constructed at 1:211 scale and tested in the 30'x30' wind tunnel of the National Research Council (NRC) in

Ottawa. These models included both the new and existing bridges in order that the effects of one on the other could be determined. There was no sign of any sudden shift in the responses of the bridges that would indicate the presence of an aerodynamic instability. The test program on the Tacoma Narrows bridges provided a unique opportunity to examine interaction effects between the two suspension bridges in close proximity to each other. No major adverse affects were found and in many cases the wind response was improved for the new bridge downwind of the existing due to turbulence created in the wake of the upwind bridge. The sectional and full-bridge aeroelastic model program proved the bridges to be aerodynamically stable and provided accurate wind loads for the design of the truss elements.

Service Load Analysis

The orthotropic deck in the New Tacoma Narrows Bridge is designed to be an integral component with the global structural system and to enhance the total system stability. The deck is stressed by global system displacements, provides composite floorbeam interaction with most of the deck plate acting as the top flange, and is an integral component of the stiffening truss top chord. Since it is not practical to incorporate detailed orthotropic deck modeling within global detailed models, the design of the new Tacoma Narrows suspension bridge used unique 2D and 3D models to analyze the global demands on the superstructure and a highly detailed 3D finite element models were used to evaluate the local demands on the orthotropic deck and floor system.

Global modeling was performed using the non-linear structural analysis program LARSA. Cables are non-linear elements, stiffened by applied tension. This means that the laws of superposition so often taken for granted for linear structures are no longer applicable, necessitating separate analysis for each load combination. Solutions are iterative in nature for each load to find the resulting equilibrium position. Various types of models were prepared, using individual sets of factored loads to generate Load Factor Design combinations for member designs and Allowable Stress Design combinations for the suspension system and fatigue analysis as follows:

- Global 3D Spine models for eigenvector/eigenvalue analysis considered the truss and deck as a single line of beam elements.
- Global 2D detailed model for live and temperature loading, with the deck and top chord modeled compositely.
- Global 3D detailed model for wind loading and floor system response to local loading with the deck modeled using plate and beam elements to simulate orthotropic behavior.

Each was performed for the initial Upper Roadway Configuration and the possibility for the Future Lower Roadway Configuration.

Modeling the orthotropic deck system in the 3D detailed models proved invaluable for erection feasibility studies by providing accurate shear lag behavior in discontinuous erection stage models. Analysis revealed significant loss of vertical, lateral and torsional stiffness during the erection process and load pathways which differ from the completed structure.

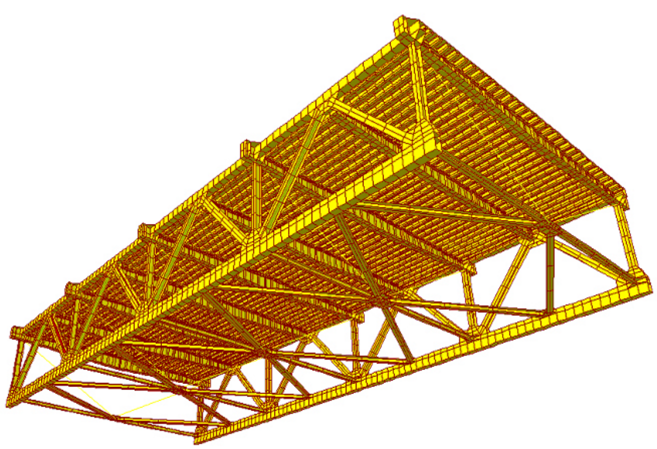

Figure 4: Detailed Local Finite Element Model

Local 3D modeling was performed using SAP2000 (see Figure 4). The local model represents a total length of 160 ft of bridge. There are 8 panels, two stiffening trusses, and 9 floor beams vertically supported by 5 suspenders in each truss segment. The longitudinal and transverse restraints at both ends are added for stability of the model. Members, such as orthotropic deck, floor beams, top and bottom chord of stiffening truss, truss verticals, diagonals, and lateral bracings, are all modeled as plate elements. The deck system is designed for HS25 live load and HS20 fatigue loading. Fatigue stresses were checked considering the criteria of both the AASHTO Standard and AASHTO LRFD Specifications.

The detailed 3D Orthotropic Deck Local Model was constructed to determine the following:

- Service load demands and deflections of the deck plate, ribs and floorbeams
- Fatigue stress range at the deck plate splice
- Fatigue stress range at floorbeam diaphragm cutout
- Fatigue stress range at floorbeam vertical stiffeners
- Fatigue stress range at floorbeam connections to the stiffening truss
- Floorbeam redundancy

Seismic Analysis

The Seattle-Tacoma area is in a region of high seismic hazard, capable of producing earthquakes of Richter magnitude eight or larger. In consideration for seismic safety, the project-specific design criteria prescribes a performance-based seismic design. Performance requirements are defined for both a Safety Evaluation Earthquake, a seismic event with a mean return period of 2,500 years, and a Functional Evaluation Earthquake, with a mean return period of 100 years. For each level of evaluation, criteria further specify the level of structural and material performance. To insure design compliance, detailed non-linear time-history structural analyses were performed. These analyses include advanced computer modeling techniques used to capture the performance of the deep-water caisson foundations and plastic deformations of the reinforced concrete tower elements. Seismic loadings did not govern the design of the orthotropic stiffening truss or the cable system except for the bottom lateral bracing immediately adjacent to the supports at the towers and the anchorages.

Wind Analysis

Design criteria relating to wind performance dictated the need for bridge sectional model studies as well as full-bridge aeroelastic model studies. Rowan Williams Davies & Irwin, of Guelph, Ontario, conducted physical wind tunnel testing and relating wind performance studies. These studies included what is believed to be the first instance where two full aeroelastic models of major suspension bridges have been tested side-by-side (see Figure 5). The testing thus provided the opportunity to examine aerodynamic interaction effects for a variety of wind parameters. Sectional model studies also allowed interaction effects to be examined. A key objective of the wind studies on the two bridges was to establish that their critical wind speeds for flutter were in conformance with the project criteria.

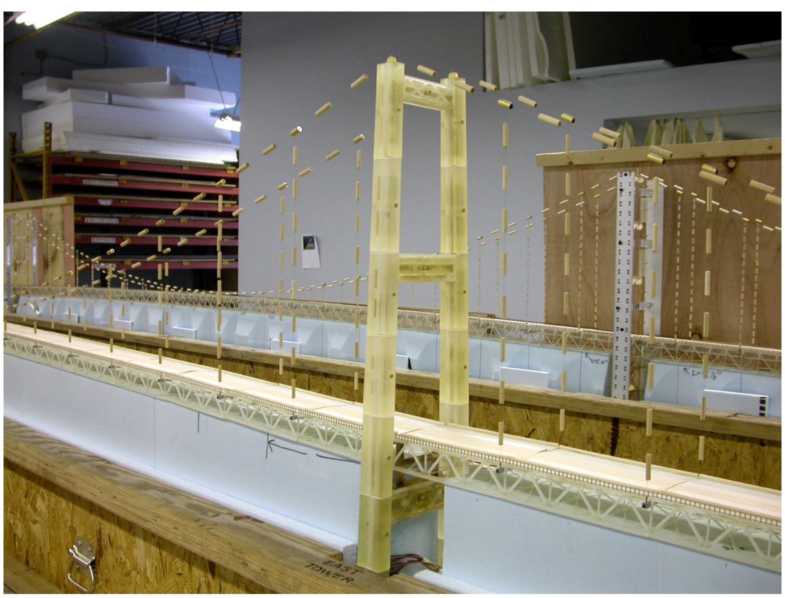

Figure 5: Full Bridge Aeroelastic Models (RWDI)

Spring mounted sectional models of both bridge superstructures were tested at a scale of 1:50 for various turbulence intensities and angles of attack. These tests were used to measure static drag, lift, and torsional moment, per unit length, normalized into aerodynamic coefficients. An important objective of the sectional model tests was also to examine the bridges' susceptibility to vortex excitation and flutter instability. No vortex induced oscillations or instability were detected as compared to criteria.

Stiffening Truss Detailing

The suspended superstructure consists of two 23'-6" deep trusses with an integral orthotropic deck, continuous from anchorage to anchorage. An orthotropic truss was selected in lieu of a box girder since it is more architecturally compatible with the existing bridge and because it allows for the installation of a future lower level with less reconstruction than a box girder. An integral orthotropic deck, as compared to a floating deck on bearings, provides superior structural efficiency by eliminating the need for a top lateral system while providing increased strength and stiffness as part of the truss top chord. This results in improved aerodynamic stability, reduced maintenance costs and reduced weight of the superstructure.

The total length of the suspended superstructure is 5,400 ft – over one mile long. The truss is continuous through the towers, with expansion joints located at the anchorages only. The cross section provides a roadway bed between reinforced concrete traffic barriers, allowing for three travel lanes, and two 10'-0" shoulders, which may be expanded to four highway lanes. With the exception of bolted splices between the fabricated bridge segments, the truss is fully welded. Typically, members are fabricated of AASHTO 270 Grade 50 steel, though extensive use of Grade HPS 70W steel in both the truss and orthotropic deck is used in regions of high member demand, particularly in the areas near the towers.

Figure 6: Rocker Links and Brackets to Truss

At the anchorages and towers, the bridge is supported by rocker links attached to the bottom of brackets on the verticals of heavily reinforced portals (see Figure 6). The links are welded cruciform sections with cylindrical, self-lubricating pins at either end. The links are 18'-0" tall at the anchorages and 19'-6" at the towers and serve to limit the vertical deflections at these points. The links resist high seismic loads in both tension and compression. At the towers, the rocker links are offset from the edges of the truss in order to allow the passage of the maintenance travelers through the tower legs, thereby limiting the required number of traveler platforms to only one upper and one lower.

The truss top chord closed box members consist of two web plates that vary in thickness from 5/8" to 3/4" ranging from 1'-10" to 2'-0" deep, and a bottom plate typically 5/8" thick. The web plates are attached to the deck plate with groove welds.

The bottom chord is typically 3'-2" deep with a 16½" wide top flange. The bottom chord also functions as an integral lower traveler rail. To accommodate this dual function, the bottom flange is 1-7/8"thick and 2'-3¾"wide, extending beyond the face of the web plates in order to provide a horizontal track surface for the traveler wheels. The bottom chord itself was also made sufficiently deep to provide the necessary bending stiffness to resist the moments induced by the traveler wheels.

The gusset plates for the top and bottom chords are integral with the chord elements and are groove welded to the edges of the web plates. Such an arrangement not only facilitates fabrication, but also reduces the weight of the structure and provides for a smooth and clean, uninterrupted appearance of the truss.

Truss verticals are located at the even panel points only, coincident with the suspender brackets (see Figure 7). The use verticals at the even panel points alone minimizes the weight of the superstructure and the number of components to fabricate. The verticals themselves are I-shaped elements with 16½" wide web plates that attach to the upper and lower gusset plate diaphragms/floorbeam extensions with complete penetration groove welds. The flanges attach to the gusset plates in the same manner. Under the future lower level configuration,

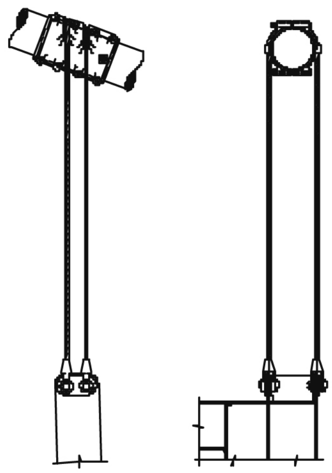

Figure 7: Type 1 Suspender Connection

where floorbeams will be attached to the bottom chord, and suspenders added at these intermediate panels, verticals will be framed in rigidly and sway bracing removed throughout to maintain required clearances.

The truss diagonals are also I-shaped elements with a 16½” wide web plate to line up with the chords and have varying width and thickness flange plates. The diagonal flanges are likewise groove welded to the gusset plates, while the web plates are fillet welded. Intermediate floorbeams are supported by the diagonals at odd panel points.

At the bottom chord level, the lateral bracing system consists of a diamond braced system, with perpendicular cross struts and crossframes at the even panel points. Material and fabrication savings resulted from the elimination of alternating struts in the bracing system. The lateral bracing consists of a combination of I-shaped and box-shaped elements, with the box shaped elements used at the locations of higher demands near the towers and anchorages. The maintenance access walkways are incorporated directly on the top flanges of the bottom lateral sections in order to reduce the weight of the superstructure and minimize the number of fabricated components.

Direct vertical support of the stiffening truss is provided by the suspender ropes, which connect to cantilever suspender brackets, serving as floor beam extensions spaced at 40’-0”.

Orthotropic Deck Detailing

The orthotropic deck of the box girder consists of a 5/8” deck plate with longitudinal 1’-0” deep hermetically sealed trapezoidal closed ribs fabricated from 5/16” thick bent plates. The ribs are supported by floorbeams that are nominally spaced at 20’-0” (see Figure 8). As a method for controlling fabrication tolerances, the plates are to be bent by break-press method only.

The floorbeams have variable-depth webs in order to reduce the weight of the superstructure, and are 3’-6” deep at the truss and 5’-6” deep at the center. The web plate is typically 3/8” thick and is longitudinally spliced with a horizontal stiffener to facilitate fabrication. Both the upper and lower portions of the web plate are groove welded to the horizontal stiffener. The floorbeam bottom flanges are also designed to support the upper maintenance traveler rails, which are designed to support the utility systems from above.

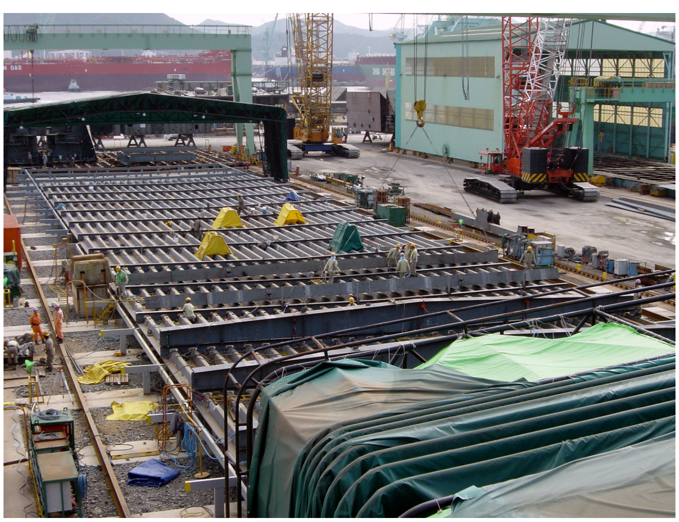

Figure 8: Completed Orthotropic Deck with Floorbeam (TNC)

A minimum 80% penetration weld between the trapezoidal rib plates and the deck plate has been specified. The objective is to attain maximum practical fusion and the desired fatigue endurance at the interface of the ribs with the deck plate. Greater penetration is not considered advantageous as it increases the potential for weld blow-through, resulting in unpredictable and inconsistent joint performance. The trough-to-deck welds are placed by an automated SAW process and overhead gantry equipment (see Figure 9).

Figure 9: SAW Gantry Welding

The design of the orthotropic deck for the new Tacoma Narrows Bridge was performed in accordance with AASHTO LRFD for fatigue as well as AASHTO Standard Specifications. The deck incorporates advances in detailing relating to fatigue endurance, as validated by full scale physical testing of a similar design used for the deck replacement on the Williamsburg Bridge in New York City. The testing program was sponsored by the FHWA and other governmental agencies with the primary objective of substantiating the predicted fatigue endurance and validating analytical models. An analytical approach validated by physical testing of a similar design was used to identify fatigue sensitive zones. Accurate identification of these zones supported the determination of the fatigue stress range for successful detailing and structure performance. A rigorous three-dimensional finite element computer model was used. The cut-out size and profile at the rib intersection with the transverse bulkhead support diaphragm follows a configuration and performance history successfully used by the designer and proven through full scale testing. These details are now incorporated into the AASHTO Load and Resistance Factor Design code. A preferred groove weld detail at the juncture of the ribs and the transverse bulkhead support diaphragms has been incorporated into the deck design. Superior performance of the detail has been validated by the referenced physical test program and was determined to have an AASHTO Category C fatigue resistance. This design meets the maximum relative deflection criteria between adjacent ribs, will result in a stress range at the deck plate splice that is less than the allowable for AASHTO Category E, and is favorable with regard to overlay performance (see Figure 10).

Figure 10: Rib Detail at Diaphragm

Internal bulkhead plates with wrap-around fillet welds are used within each closed rib trough at support points. This design improvement has been demonstrated to be effective in reducing out-of plane deformation of the rib plates, resulting in agreeable fatigue performance.

Transverse deck-to-deck welds are required every 40’-0” in the deck plate. Bolted field splice connections are specified for the rib with an adjacent complete penetration welded splice for the deck plate. This approach results in favorable fatigue endurance.

Center Tie

At the center of the main span, the superstructure is secured to the main cable via the center tie. The center tie consists of rigid diagonal members composed of fabricated I-sections. These members frame into a bracket designed to be integral with the orthotropic deck and a pair of gusset plates pinned to the center tie cable band. The vertical member of the center tie is designed simply as a suspender rope. This center member supports the dead weight of the bridge, leaving the diagonal members stressless under dead load. This type of configuration eliminates dead load bending on the elements and facilitates fabrication and erection as compared to an all-rigid type (see Figure 11).

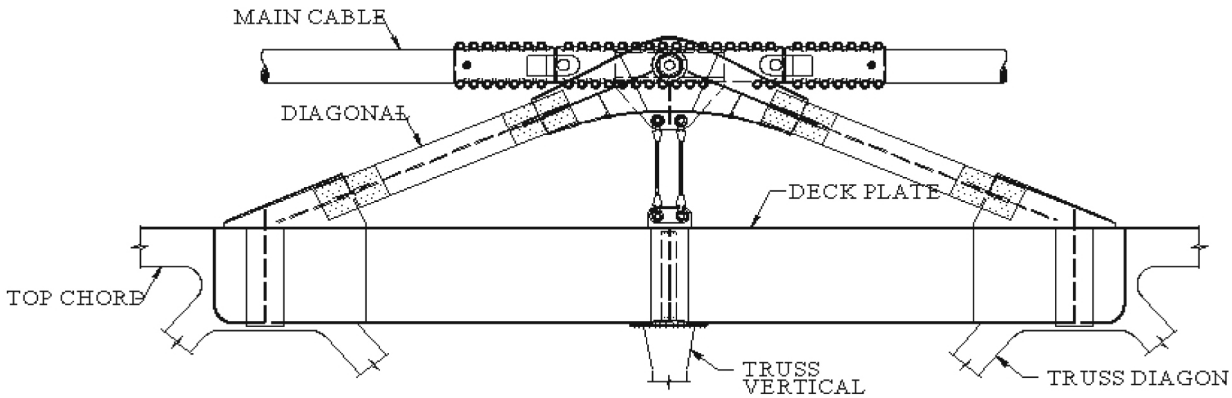

Figure 11: Center Tie

Since the center tie cable band needs to be long in order to resist the high seismic demands, it has been designed as an articulated group of three cable bands. The center band has a threaded lug cast integral with the band that serves as the connection point between the band and the diagonal gusset plates. The center tie cable band is also machined to provide a bell-mouth radius into the ends of the cable band to allow for some rotation of the main cable.

Provisions for Future Double Decking

In order to permit the bridge to be outfitted with a second deck in the future, very specific requirements were included in the project design criteria. With the understanding that a secondary cable anchored to new anchorages would be added to accommodate the additional load placed on the suspension system, the design of the suspension system was unaffected by these provisions. However, in order to accommodate the increased reactions at the tower, the towers and caissons were designed for the future loads. Additionally, the anchorages were designed to accommodate the passage of the future lower level between the splay chambers of the new bridge.

The superstructure design was governed in many cases by the geometric restrictions and traffic loads anticipated for the future lower level. The depth of the truss was set to accommodate future truck and/or LRT clearances and the top and bottom chords and truss diagonals were designed to accommodate the future lower level without additional reinforcement. The bottom lateral bracing and cross frames are envisioned to be removed and replaced with an orthotropic deck integral with the bottom chord, similar to the upper deck.

Fabrication

Fabricators were part of a project Task Force team, which also included TNC, WSDOT and Parsons. The design team solicited fabricator input throughout the design process. While fabrication is taking place overseas, TNC has a permanent presence in the shop and yards to maintain oversight. The designers have made several shop visits to provide technical support to TNC and the fabricators since the process began.

The bridge sections are being fabricated in Korea by Samsung Heavy Industries (SHI), under subcontract to a Joint Venture of Nippon Steel and Kawada Bridge (NSKB). The bridge will be fabricated in 46 segments, typically about 120 ft long. They are scheduled to be shipped across the Pacific Ocean, stacked four segments high, on three SWAN class vessels. All steel will be fully coated in Korea to protect against salt intrusion during transit. Each segment, weighing approximately 400 tons, will be hoisted into place from a pair of gantries mounted atop the main cables. Sections near the anchorages will be swung (“trapezed”) into place and/or slid into position on skids. The segments will be painted and completely outfitted with the upper traveler rail, utility supports, and access platforms in the fabrication shop to expedite completion of the finished bridge (see Figure 12).

Figure 12: Completed Bridge Segment (TNC)

Lessons Learned

The Design/Build project delivery system was an efficient way to procure the facility. The project clearly illustrated the value of communication in delivering a quality product. These practical forms of communication included:

- Lively Task Force meetings effectively used to resolve issues to mutually agreeable solutions
- Contractor representatives working alongside the designers to assure their input is continuously reflected in the design
- Fabricator visits to the design office and designer visits to fabricators
- Comment resolution forms that recorded not only comments, but actions, explanations, and written discussion

Through cooperation and mutual respect, any issues that arose were quickly resolved.

On a technical note, the use of HPS steels appears to be more easily accommodated by the industry as time goes on. Proper consumables, care at interfaces with other materials, and clear procedures make for an easy fabrication process.

Conclusions

Design of the new Tacoma Narrows Bridge has set a new standard in modern suspension bridge design in the United States, particularly in regard to composite orthotropic deck / truss design. Some of the key elements of the design are:

- Fully welded stiffening truss with composite orthotropic deck.
- Use of high strength steel (HPS 70W)
- Integration of traveler rail into the bottom chord
- Use of truss verticals at even panel points only
- Articulated center tie design
- Finite element analysis approach was adopted which full-scale physical testing previously validated.
- Innovative truss support at the towers

As a result, the new Tacoma Narrows Bridge sets a high standard in suspension bridge design and detailing, serving as an example to the next generation of bridge designers and constructors.