THE DESIGN OF A SHARPLY CURVED STEEL GIRDER BRIDGE SERVING PORT NEWARK, NJ

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BIOGRAPHY

Mr. Preston Vineyard is a lead structural engineer and Professional Associate with Parsons Brinckerhoff's New York office. He has 10 years of design experience of various complex and conventional bridge types including multi-girder bridges, arches and cable-supported bridges. Mr. Vineyard served as a structural design engineer for this project and was responsible for the design of various components of the bridge.

Mr. Ruchu Hsu is a Principal Professional Associate with Parsons Brinckerhoff's New York office. He has been the project engineer responsible for the design of numerous complex bridges including the design of 4 cable-stayed bridges. Mr. Hsu served as the project engineer for this project

Mr. Yu Shing Wong is a Senior Engineer with the Port Authority of NY & NY, Engineering Department. He is the project engineer for the Corbin Street Flyover Bridge.

Mr. Owen Lee is a Principal Engineer with the Port Authority of NY & NJ, Engineering Department. He is the supervising structural engineer for ports projects, including the Corbin Street Flyover Bridge.

Dr. WooSeok Kim is an assistant professor of Chungnam National University, Daejeon, South Korea. Dr. Kim was with Parsons Brinkerhoff's New York office and served as a design engineer responsible for analysis and design of the curved spans for this project.

SUMMARY

As a part of the ExpressRail Corbin Street Intermodal Rail Support Facility Program, the Corbin Street flyover Bridge located in Port Newark, New Jersey, required a significantly tight curvature, not typical of common curved bridges. There were many design challenges in this project. This paper focuses on the development of an innovative controlled floating bearing system in order to accommodate and control the thermal expansion and contraction of the superstructure. The curved steel I-girder bridge with an extremely small radius of 169 ft is comprised of 7 continuous spans with a total length of 543 ft. The superstructure is comprised of 7 girders in cross section and carries 2 lanes of traffic. These dimensions result in a horseshoe shaped structure with a curvature of 183 degrees. Extensive analyses were conducted to identify the center of thermal movement to determine the alignment of bearing guides and to minimize the thermal forces induced on the piers. This study also evaluated substructure performance for horizontal loads such as wind and seismic loading. The innovative controlled floating bearing system is expected to achieve low initial and future maintenance costs, a reduction in the number of expansion joints and lower moment demands in the substructure and foundations from horizontal loads. The bridge is currently under construction and is expected to be completed at the end of 2012.

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Introduction

The new Corbin Street flyover bridge will provide a critical link between the Port Newark Container Terminal (PNCT) and the PNCT Intermodal Railroad Yard in Newark, NJ. The Port Authority of New York and New Jersey (PANYNJ) structure spans over Corbin Street as well as existing railroad tracks. The flyover is a dedicated bridge for the PNCT operations and the traffic on the bridge will primarily be yard tractors pulling trailers of various lengths between the container terminal and the railroad yard.

Parsons Brinckerhoff (PB) was retained by the PANYNJ to provide preliminary and final design services, as well as support services during construction. The bridge is currently under construction and is expected to be completed in 2012.

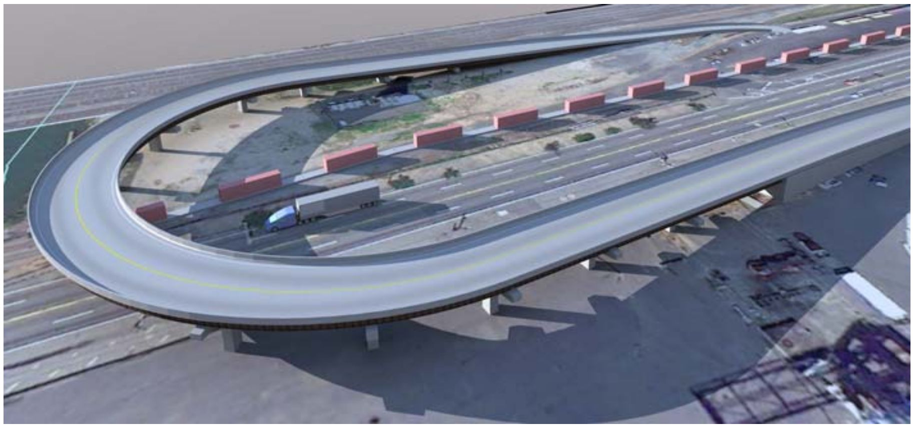


Figure 1: Rendering of the new Corbin Street flyover bridge

The geometric constraints of the site require a sharply curved bridge with a centerline radius of only 169 feet. The bridge will continue on tangent sections to meet the abutments, so the overall elevated bridge will form a 1,037-foot long horseshoe shape. The bridge will connect to the PNCT by way of a 375-foot-long east ramp structure consisting of modular retaining walls placed above a geogrid-structural mat supported on timber piles, and to the 126-foot-long west ramp structure consisting of retaining walls supported on a concrete slab founded on steel pipe piles. The elevated curved structure consists of two 18-foot lanes with 3.5-foot shoulders. The wider 18-foot lane widths, along with a roadway deck cross slope of 3.4% will assist the tractor-trailers in navigating the tight curve of the flyover. The lanes transition from 18 to 12 feet on the approach ramp tangent sections.

There are a number of constraints at the site including a Federal Aviation Administration (FAA) ground radar tower, Corbin Street and active railroad tracks. Additionally, there are numerous existing utilities at the site, including fiber optic cables for the FAA radar tower, fuel pipelines, a 30- inch diameter gas main, an electrical conduit bank, 18 and 36 inch diameter drainage lines, a 24-inch diameter water main and overhead telephone lines. These constraints dictated the locations of the piers and span lengths for the superstructure as well as the type of foundation to be used. The site constraints also dictated construction methods since delivery of material to the site, construction activities and superstructure erection must be performed in a manner that limits impact on existing operations. To minimize the foundation footprint, single column hammerhead piers supported by single drilled shafts were selected.

Design of the new flyover structure presented many design challenges. However, this paper primarily focuses on the design of the curved spans. The curved portion of the flyover is comprised of 7 continuous spans totaling 536 feet in length. The structure curves a total of 183 degrees, which results in a horseshoe shape. The horseshoe shape and sharp radius of curvature induces different behavior compared to a typical curved girder bridge. An innovative controlled floating bearing system was developed in order to accommodate thermal expansion and contraction. Extensive analyses were conducted to select the optimal center of thermal movement in order to determine the alignment of bearing guides and to allow the bridge to freely expand and contract. The controlled floating bearing design minimizes the number of expansion joints, which not only simplifies the construction, but also minimizes future maintenance.

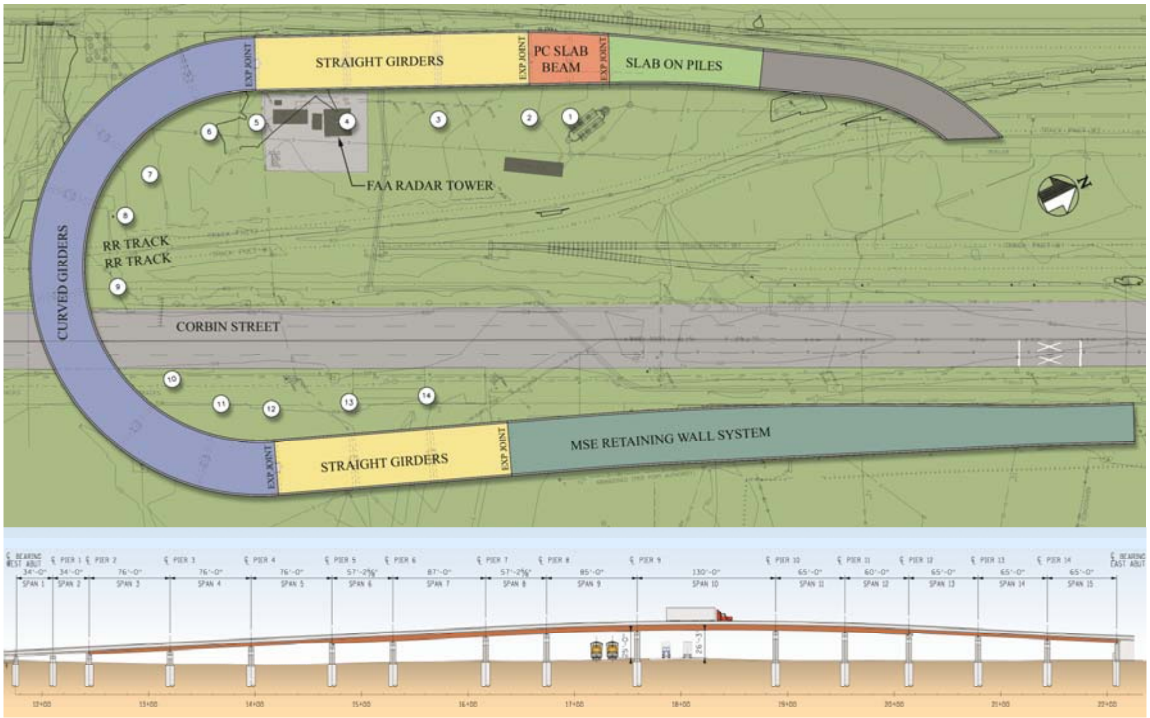


Figure 2: Overall project plan and elevation

Substructure Design

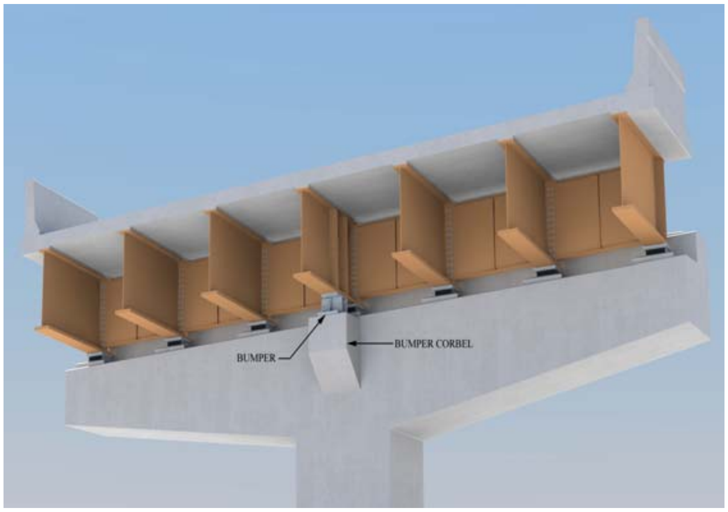


Figure 3: Hammerhead Pier (Pier 12 shown)

Because of the numerous site constraints including active railroad tracks and underground utilities, it is critical to minimize the overall footprint of the new Corbin Street flyover. The solution that provided to smallest substructure footprint utilizes single column hammerhead piers (see Figure 3) supported by single drilled shafts. The drilled shafts for the project extend through the soil deposits and utilize rock sockets to achieve their capacity.

As previously mentioned, the project site also contains an FAA ground radar tower. The ground radar system is critical for safe and uninterrupted operations at Newark International Airport. Construction of the proposed Corbin Street Flyover structure requires the use of heavy construction equipment and installation of drilled shaft foundations in close proximity to the radar station. It was essential that vibrations generated by the construction operations, including the installation of the drilled shaft foundations, not adversely affect or interrupt the operation of the radar system. As a result, project specific ground vibration limitations and vibration monitoring procedures were required during construction. The foundation construction near the FAA tower has been completed and no excessive vibrations were detected.

Superstructure Design

As previously described, the curved portion of the superstructure is comprised of 7 steel I shaped plate girders, which are continuous over 7 spans of various lengths. The girders are composite with a 9½ inch thick reinforced concrete deck. All the curved steel girders have a 4'-6" constant depth web with variable dimension flanges. The steel I-girders are a suitable solution for the Corbin Street flyover since they can provide a shallow superstructure that can accommodate the sharply curved geometric requirements. See Figure 4 for an illustration of the bridge typical section.

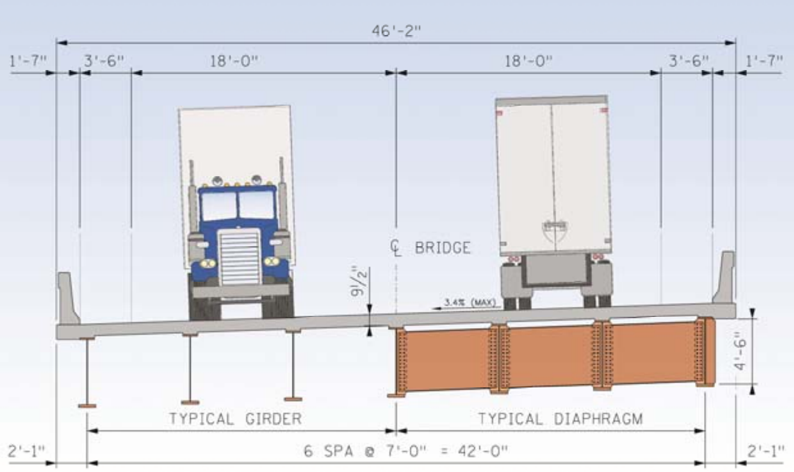


Figure 4: Bridge typical section

The pier locations were dictated by the numerous constraints of the existing conditions. The resulting spans are unequal in length and the 130 ft long span over Corbin Street, which is 1.5 to 2.5 times longer than other span lengths, increases the complexity in predicting and analyzing curved bridge responses.

Figure 5: Photo of erected curved girders

The curved radius of 169 ft along the bridge centerline nearly reaches the extreme bound set by AASHTO Guide Specifications (1993) of 150 ft. The sharp horizontal curvature significantly increases inherent torsion and warping in a curved girder. Because of the sharp curvature, top and bottom lateral flange bracing is necessary. The lateral flange bracing creates a pseudo closed section, which greatly increases the superstructure's torsional capacity to resist the forces induced by the curvature.

Due to the complexity of the structure, a refined structural analysis was warranted. The global analysis of the bridge was carried out using a three-dimensional (3D) structural model, including explicitly modeled foundation elements with non-linear springs to simulate the soil properties. The superstructure was modeled using beam and shell elements. The webs of the curved steel girders and the concrete deck were modeled using shell elements, while the girder flanges, diaphragms, flange lateral bracing and cross frames were modeled using beam elements with prismatic section properties. The substructure components were modeled using beam elements with prismatic section properties. The global analysis was conducted using the general analysis program LARSA 4D. Figure 6 shows a graphical view of the structural model.

The 3D structural model was used to simulate the behavior of the structure during various stages of construction as well as in the structure's completed state. As with most continuous span bridges, the concrete deck of the Corbin Street flyover is placed in multiple pours. Because of the sharp curvature and span arrangement, the flyover is particularly sensitive to the deck casting sequence. A detailed analysis was conducted to determine a suitable deck casting sequence that would not result in any girder uplift at the bearings. The analysis also determined the load effects, locked in stresses and deformations of the girders, lateral bracing and diaphragms during deck placement. This analysis is critical since the effects of the deck placement can often control the design of these members. By explicitly modeling the diaphragms and flange lateral bracing, the actual resulting member forces and deformation can be extracted directly from the model.

As required by the project design criteria, future deck replacement while maintaining one lane open to traffic must be feasible. Anticipated deck replacement construction stages were simulated and evaluated using the structural model. As expected, the governing loading case occurs when the inside half of the deck is removed and vehicle live load is present on the outside lane. The analysis confirmed that future deck replacement is feasible and the members have been designed accordingly.

The structural model simulating the flyover in its completed state was then utilized to predict the bridge's response to transient loads such as vehicle live load, wind load, earthquake and superimposed deformations caused by temperature variations. The bridge's response to temperature changes is particularly unique and is discussed in more detail below.

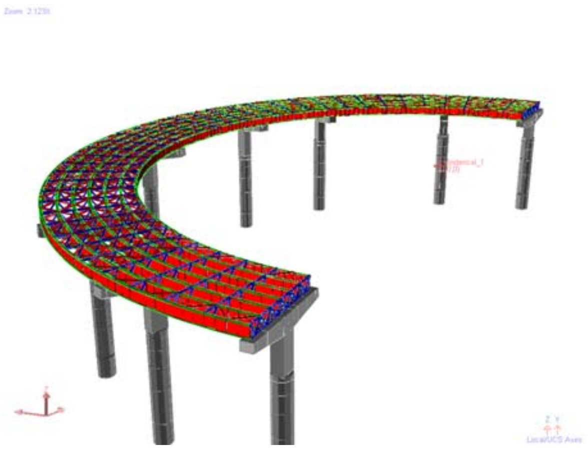


Figure 6: Graphical representation of the 3D analytical model

Thermal Behavior

The 541 ft long curved girder portion of the Corbin Street flyover has been designed to have only two expansion joints. The joints are located at the points of tangency of the horizontal curvature, which coincides with Pier 5 and 12. Having only two expansion joints has numerous benefits including a reduction in future maintenance and improved structural performance. However, the relatively long unit significantly increases the thermal movement of the structure. When this thermal movement is combined with the sharp curvature, the bridge behavior is further complicated. As a result, design of the bridge essentially requires controlling this thermal movement to minimize the additional loads induced by thermal restraint. Particular attention has to be paid to the thermal movement on bridges with sharp curvature because the bridge translates in both the radial and tangential direction. Excessive lateral thermal forces at supports can result if only tangential movement is permitted.

Several bridge articulation configurations were evaluated during the design process. The configurations include fixing a single pier, fixing all piers, and two different floating systems. Each of these articulation configurations are discussed in detail below.

Traditional curved girder design generally provides one fixed support (restraint to all translations). All other bearings are guided toward this fixed bearing so that all other bearings can expand and contract toward this fixed bearing. Thus, this fixed bearing becomes the center of thermal movement (CTM). For a curved bridge that has a small number of spans and is short to medium in bridge length, this approach is appropriate. However, this boundary system increases the thermal expansion length as the bridge length is increased. In addition, one fixed pier is required to resist all the structure's lateral loads and the thermal movement directions at the expansion joints are not tangential, but skewed. Figure 7 presents traditional bearing system and displacement directions.

Because of its sharp curvature and long expansion length, the traditional curved girder design articulation methodology is not ideal for the Corbin Street flyover bridge.

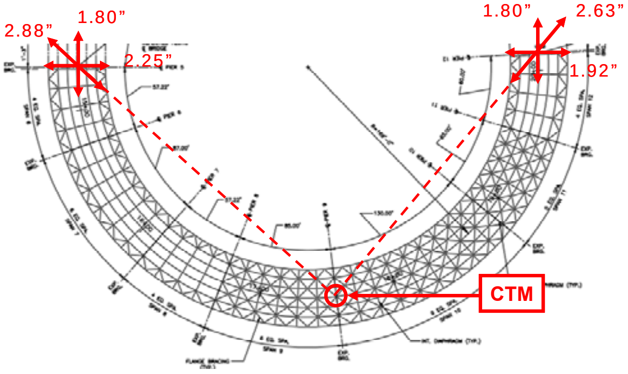


Figure 7: Traditional bearing system

Providing full restraint to all translation at each pier was evaluated during the design process. This design approach relies on the flexibility of the substructure to accommodate the thermal displacements. Although this design approach is often utilized, it is not suitable for the Corbin Street flyover because the relatively short piers and the thermal movement results in lateral displacements of the piers in excess of the limitations set in the project design criteria.

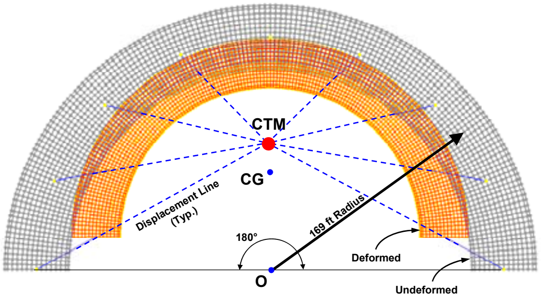


Figure 8: Free floating bearing system

Since the sharply curved structure primarily translates in a radial direction, a free floating bearing system allowing free radial displacement toward the center of thermal movement was also investigated. Figure 8 presents the thermal movement direction of a free floating boundary system. All thermal movements expand and contract toward the CTM. In theory, this floating system induces minimal forces due to thermal displacement since the movement is not restrained. The performance of this system relies on the accurate determination of the CTM.

In the case of the Corbin Street flyover, which has numerous piers and bearings, the CTM determination is quite difficult since the varying pier and bearing lateral stiffness causes the CTM to shift. In addition, each bearing has a unique orientation to guide it towards the fictitious CTM and the shifting CTM causes frequent engagement in the bearing guides. Similar to the traditional bearing alignment, the free floating bearing system also has skewed thermal movement at the expansion joints. Because the complex bearing orientation and the resulting skewed thermal movement at the expansion joints, the free floating bearing system is determined to not be practical for this structure.

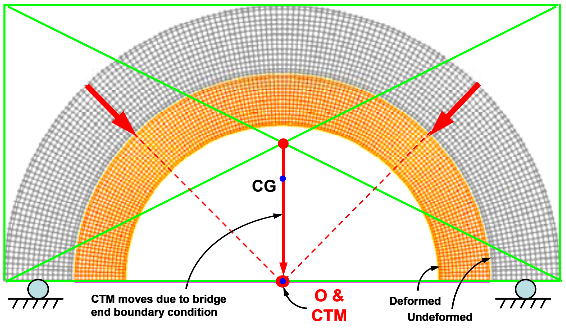
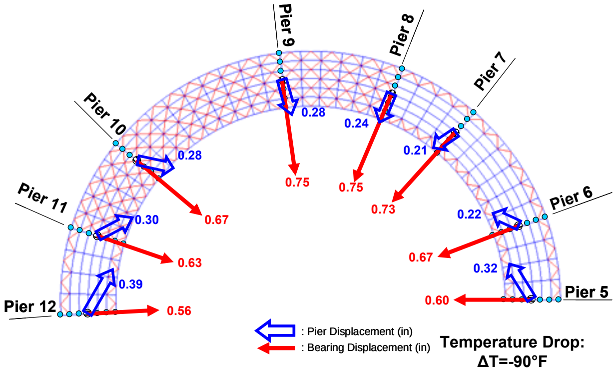


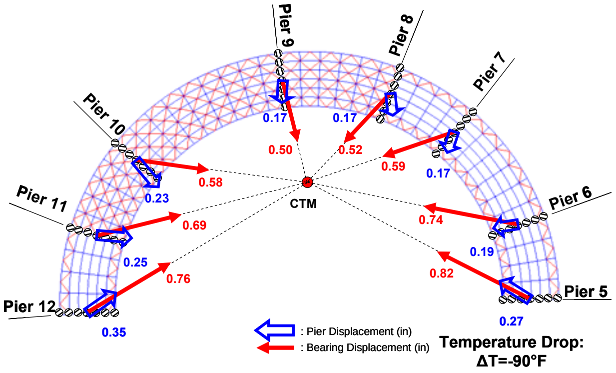
Figure 9: Controlled Floating Bearing System

To achieve the goal of minimizing the thermal forces on the structure as well as to provide a bearing system that is easy to construct and maintain, a controlled floating bearing system with simple guided elastomeric bearings was developed for the Corbin Street flyover. The controlled floating bearing system (as shown in Figure 9) is similar in concept to the free floating system, with the exception of the boundary conditions at the expansion joints. When the tangential displacement at the expansion joints is restrained, the CTM at is located at the center of the curvature (see Point O in Figure 9). All thermal displacements in the controlled floating bearing system are tangential to the curvature at any given location. All bearings are oriented to the concentric center of the bridge curvature and aligned to be perpendicular to the pier hammer head to simplify construction. The tangential displacement at the expansion joints is restrained by use of a tangential bumper system, which is described in detail below. See Figure 11 below for an illustration of the bearing fixities.

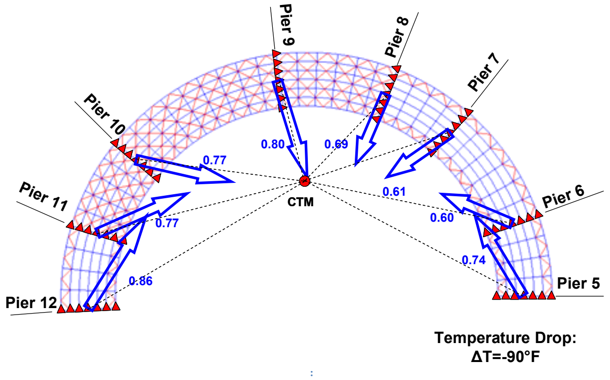
A relative comparison of the bearing and pier displacements for each of the evaluated articulation configurations is depicted in Figure 10.



Controlled Floating Bearing System



Free Floating Bearing System



Fixed Bearing System

Figure 10 – Thermal Movement Comparison

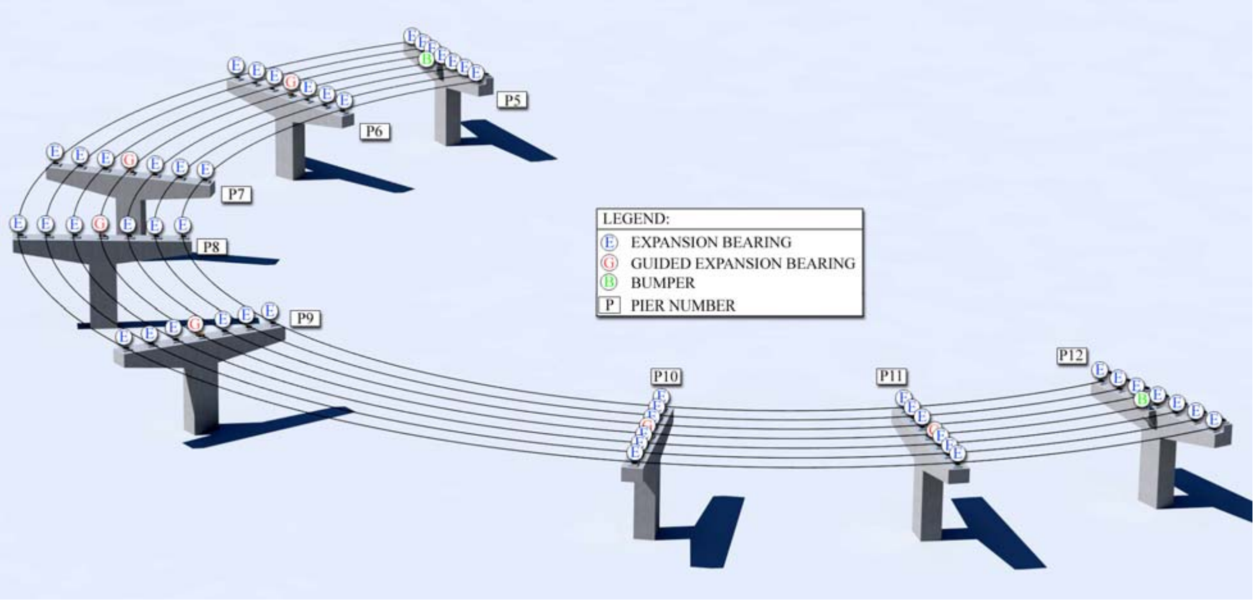


Figure 11: Bearing Fixities

To achieve the controlled floating articulation concept, longitudinal bumpers are required to resist the tangential restraining forces at the expansions joints, but still allow free translation in the radial direction. The bumpers consist of a steel bracket mounted to a concrete corbel extending from the pier cap and a steel tongue bolted to the bottom of the center girder as shown in Figures 12 and 13. Elastomeric bumper pads are vulcanized steel plates, which are bolted to the bracket on the pier. Stainless steel plates are attached to the bumper pad and the steel tongue. As the bridge expands, the tangential force from the superstructure engages the tongue and bracket. The elastomeric bumper pads evenly distribute the force to the stainless steel plates, which provide the sliding surface for the radial expansion.

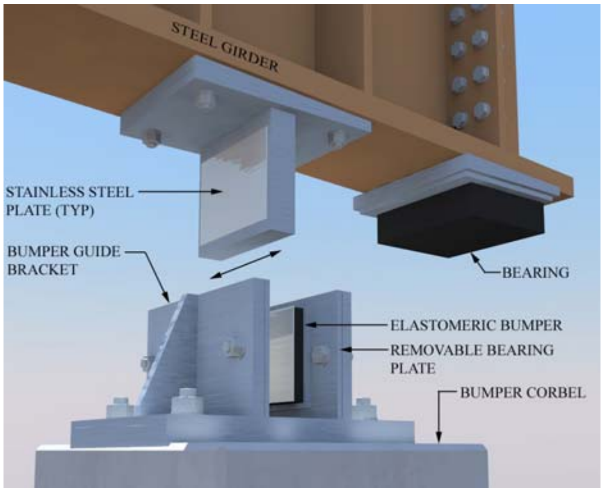


Figure 12 Bumper Assembly Illustration

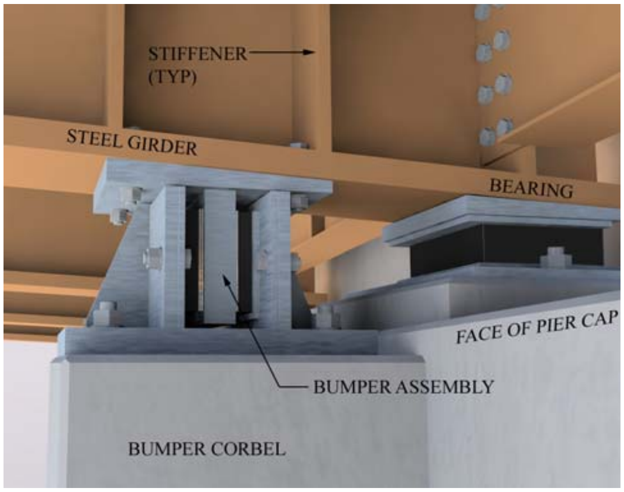
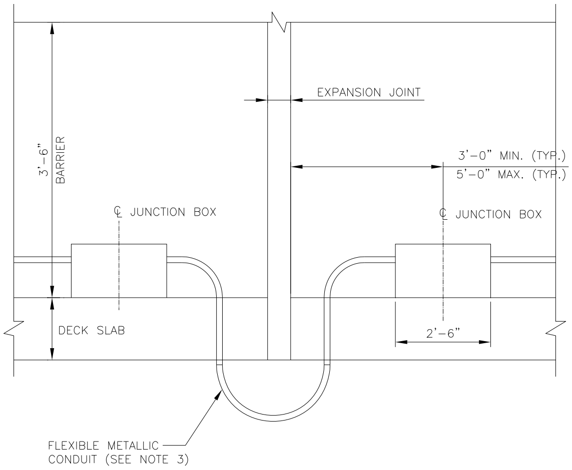
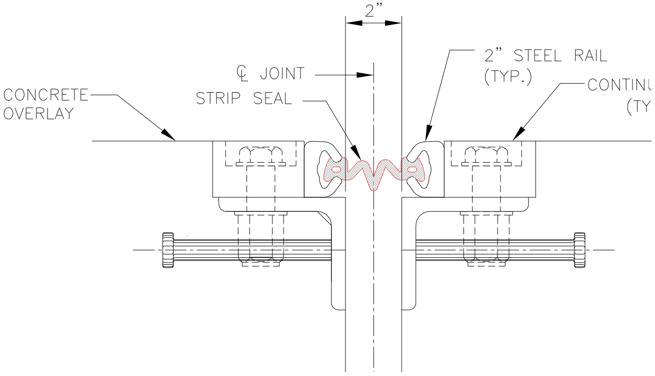


Figure 13 Bumper Assembly

Since the controlled floating articulation system allows radial displacement, the expansion joints and utility conduits in the barriers must also accommodate the radial displacement. A conventional strip seal expansion joint system was selected and sized to accommodate the nearly +/-1" of radial displacement. In the case of an extreme event that results in very large radial displacements, the rubber strip seal gland may overextend and tear. A removable expansion joint rail system, which was provided by PANYNJ, simplifies the replacement of the rubber gland. In order for the rigid conduits to accommodate the radial movement, the conduits extend out of the deck slab and transition to a flexible metal conduit. Illustrations of the conduits and expansion joint system can be seen in Figure 14.



(Conduit Expansion System)



(Strip Seal Expansion Joint)

Figure 14: Expansion Joint System

In addition to allowing the structure to accommodate thermal displacements, the bearing and bumper system must also transfer wind and seismic forces between the superstructure and the substructure. In the case of the Corbin Street flyover the 56 elastomeric bearings located along the curved structure provides lateral support. For added measures, additional bearing guides are provided at each pier.

CONCLUSION

The challenges of the Corbin Street flyover bridge, such as its complex thermal articulation and sharp curvature, have been successfully accomplished by careful consideration of the details and effective teamwork between the engineering team and the bridge owner. The use of curved steel girders was essential in providing an effective solution to the difficult project site constraints. Once completed, the flyover will provide a critical link and improve operations at the Port Newark Container Terminal.

ACKNOWLEDGEMENTS

Owner: The Port Authority of New York and New Jersey
Contractor: George Harms Construction Co., Inc,
Design Consultant: Parsons Brinckerhoff, Inc.

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