When South Carolina decided to replace the superstructure of a signature swing bridge, its requirement that the crossing be closed for no more than 10 days

RAPID TURNAROUND

seemed daunting. By designing the replacement segments to closely resemble the originals and constructing much of the new superstructure off-site, the design/build team—despite rain, wind, and snow—was able to provide the community with a nostalgic crossing with minimum delay.

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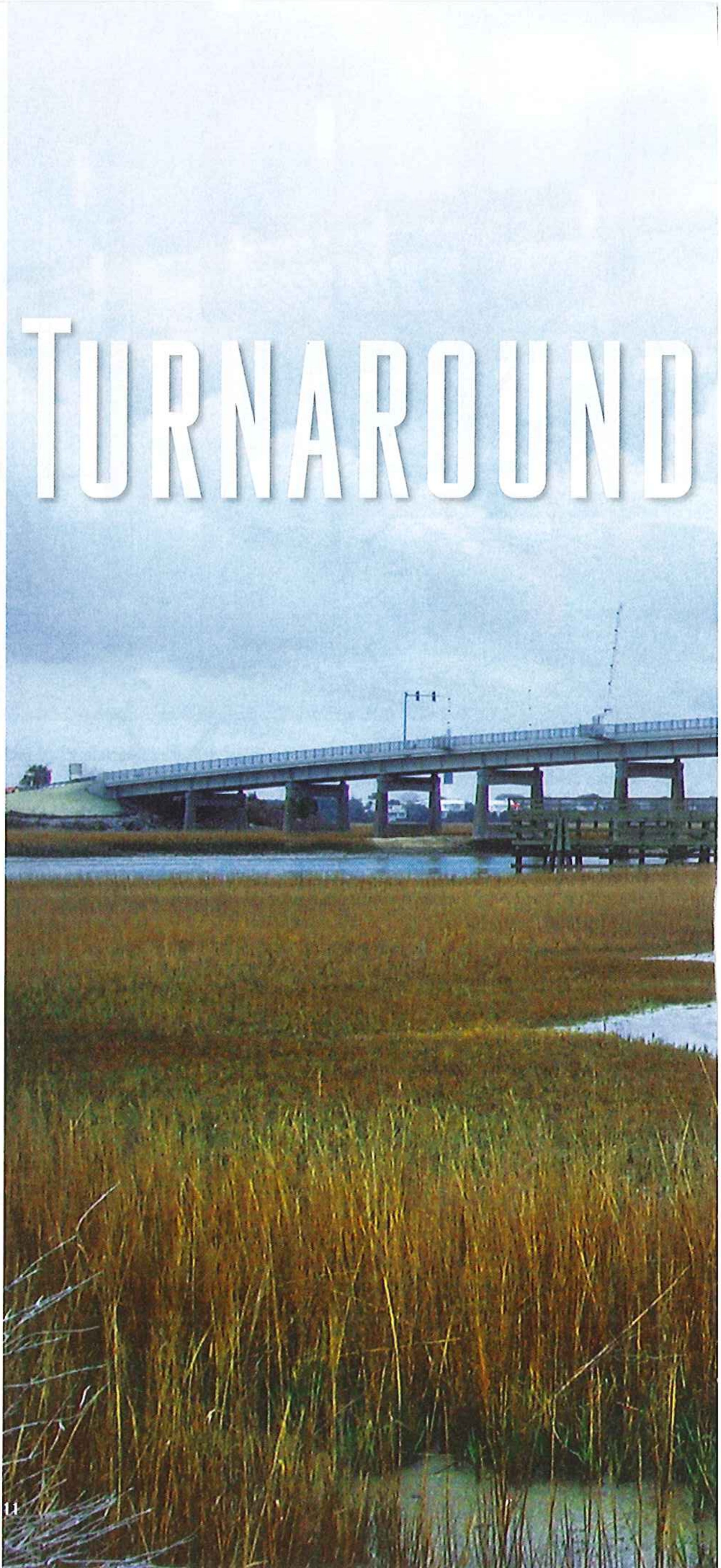
By Timothy J. Noles, P.E., M.ASCE



CONSTRUCTED IN 1945, the Ben Sawyer Bridge spans the Atlantic Intracoastal Waterway between Mount Pleasant and Sullivan's Island just southeast of Charleston, South Carolina. The Warren swing truss crossing was named for the highway commissioner and executive director of the South Carolina Highway Department (now the South Carolina Department of Transportation [SCDOT]) from 1926 to 1940. The bridge consisted of 12 steel girder approach spans, 6 on either side of the

Warren truss swing span, which crossed the navigation channel. The swing span extended 247 ft from rest pier to rest pier with a pivot pier in the center. It provided a 45 ft vertical clearance in the closed position and infinite clearance in the open position. Its Warren truss was supported on reinforced-concrete piers founded on timber piles. The bridge provided one 12 ft lane for vehicular traffic in each direction in addition to 2 ft 6 in. safety curbs on each side of the roadway.

The bridge provided the only access to Sullivan's Island, a barrier island and summer resort community with more than 2,000 residents, and to the neighboring Isle of Palms until the Isle of Palms Connector Bridge was constructed, in 1992. That project was undertaken after Hurricane Hugo, a storm of category 5 that struck in 1989, blew the Ben Sawyer Bridge's swing span from its center bearing. The swing span was eventually placed back on its pivot pier and provided 22 additional years of service, but a replacement bridge was eventually necessary because of the toll that the coastal salt air had taken on the steel superstructure of the swing span and approach spans. The bridge railings and concrete deck also were severely corroded, and the deterioration of the superstructure eventually required the SCDOT to limit the weight of trucks crossing the bridge to 20 tons.

In 2006 the SCDOT initiated a study on replacing the bridge and sought input from nearby communities in the process. The SCDOT favored a high-level fixed bridge, but local residents wanted to see their signature bridge restored. An engineering study conducted by the Columbia, South Carolina, office of Parsons Brinckerhoff determined that although the substructure was in good condition and could be reused in a rehabilitation, the superstructure was in poor condition because of the corrosion of the swing span trusses and the floor system and the formation of fatigue cracks in the steel stringers of the approach spans.

The new swing span features a Warren truss with midtruss bracing, even though such bracing was only structurally required at the portals to the truss. The elevated control house is larger than the original but retains the distinctive octagonal shape.

COURTESY OF PCL CIVIL CONSTRUCTORS, INC.

Residents of the area, which includes Mount Pleasant, Isle of Palms, and Sullivan's Island, viewed the Ben Sawyer Bridge as a landmark of historical importance and as a symbol of the charm and tradition of the community and requested that the structure be restored or replicated to the greatest extent possible. The community favored a new bridge only if its design incorporated the following distinctive features of the old one: cantilevered brackets on the approach spans' plate girders, concrete posts and steel picket railings, a swing span consisting of a Warren truss with midtruss bracing, a vertical profile similar to that of the original, and an octagonal control house mounted on the swing span above the roadway.

The improvements required by the SCDOT in its request for proposals (RFP) included a widening of the roadway deck from 24 ft to 28 ft, including a single 5 ft 6 in. sidewalk on the west side of the roadway; bridge rails meeting the appropriate strength requirements; and compliance with the load and resistance factor design (LRFD) codes for bridges and movable bridge operating systems formulated by the American Association of State Highway and Transportation Officials (AASHTO) and set forth in the second edition of the *AASHTO LRFD Movable Highway Bridge Design Specifications.* The existing substructure, together with any newly constructed elements, would have to meet these codes.

Built in 1945, the original Ben Sawyer Bridge included 12 steel girder approach spans and a Warren truss swing span above the navigation channel.

PHOTOGRAPH BY T.J. NOLES

The SCDOT decided to proceed with the rehabilitation project but recognized that if conventional construction practices were used, any such project would require a lengthy detour—one of more than 10 mi to the Isle of Palms Connector Bridge—for a prolonged period. In view of the effect that such a detour would have on local businesses on both sides of the bridge, it was realized that the local community would be unwilling to support it for very long. So the SCDOT required that the bridge closure not exceed 10 days.

To promote innovative and unique construction techniques and engineering during all phases of the project and to ensure that bidders would be properly qualified, the SCDOT advertised the project as a design/build contract in May 2008. The design/build team was required to use innovative accelerated bridge construction methods to meet the bridge closure requirement of 10 days. PCL Civil Constructors, Inc., of Tampa, Florida, achieved the highest technical score and submitted the lowest bid amount—$32.5 million—to win the contract. The contract was paid by the Federal Highway Administration.

PCL assembled a proven team to carry out the design/build contract. The PCL staff members chosen for the team are considered industry experts in both movable bridges and bridge replacement projects, and they were assigned to lead the design/build team. The team also included the Sunrise, Florida, office of Hardesty & Hanover, LLP, as the principal bridge designer and the Columbia, South Carolina, office of Florence & Hutcheson, Inc., as the civil engineering firm. Florence & Hutcheson also supported Hardesty & Hanover and PCL with permitting, geotechnical engineering, utility design services, and maintenance of traffic services. Civic Communications, Inc., LLP, a Charleston public relations firm, managed community relations and public information distribution. The team also included key subcontractors and suppliers that were viewed as critical to the success of the project.

The technical proposal for the rehabilitation met the SCDOT's key criteria, which were to maintain an appearance similar to that of the existing bridge, retain the vertical profile, keep the community properly informed of developments, and adhere to the scheduling and bridge closure requirements. The new bridge superstructure was designed in accordance with the requirements of the RFP, the AASHTO LRFD codes mentioned above, and the SCDOT's technical specifications, special provisions, bridge design memorandums, and other design guidelines. The dead load of the replacement superstructure was minimized as much as practical because it was to be supported on the existing substructure, which was not designed to carry any additional loads. New structural steel components with increased strength (grade 50), along with lightweight concrete (115 lb/cu ft), were used to achieve this goal.

The substructure was determined to be in remarkably good condition with no signs of deterioration. Concrete cores were taken during the development of the RFP, and these revealed strengths of up to 9,000 psi. A preliminary seismic analysis also was conducted prior to the RFP to determine the seismic event that the substructure was capable of resisting. The timber pile foundation was required to meet the AASHTO LRFD code for the heavier superstructure with the use of isolation bearings; if this was not possible, a retrofit would be required.

The bridge is classified by the SCDOT as "essential" and has a seismic performance category of B, meaning that it has a long-period acceleration of 0.1*g* to 0.3*g*. The RFP specified that the earthquake to be used for functional performance would have a return period of 500 years. In analyzing the bridge, no live load was used in any of the seismic load combinations. The pile and footing elements were explicitly modeled with the appropriate representation of the effects of the nonlinear interaction between soil and structure.


The new approach spans were prefabricated directly west of the existing structure on temporary bents and access trestles. The new swing span was erected off-site at the Port of Charleston terminal and transferred to the site by barge. At high tide, hydraulic jacks mounted to the barge lifted the new swing span into place.

FLORENCE & HUTCHESON CONSULTING ENGINEERS

A three-dimensional model of the bridge, from abutment to abutment, was created using SAP2000 software (produced by Computers & Structures, Inc., of Berkeley, California) and was analyzed using the seismic input loads called for in the technical specifications. This included a response spectrum analysis as well as a time history analysis. It was determined that the existing substructure would be adequate for the prescribed seismic event if isolation bearings were added. Some of the struts of the piers showed an inelastic response, but there were no catastrophic failures of the substructure during the model runs. It was also required that the swing span's lateral displacement not rack, or sway together, with the approach spans' superstructure during an earthquake. The swing span pivot bearing was designed to resist a seismic load of more than 350 kips.

Pile-driving data and soil borings from the original bridge construction were used to determine the load capacities of each pile so that it could be determined whether or not the foundations were within the acceptable resistance factors. Although the foundations overall provided adequate capacity, certain individual piles showed resistance factors, which represent a percentage of the ultimate load capacity, of between 0.4 and 0.7. Although these figures do constitute a factor of safety, they are above the LRFD allowance of 0.4. However, AASHTO allows a resistance factor of up to 0.6 if a pile-driving analyzer is used. For this reason, timber test piles were driven to obtain data from a pile-driving analyzer. Resistance factors of 0.7 were found on individual piles of the north abutment. For this reason, the SCDOT required that additional piles be driven to support the abutments, mitigating the additional loads that would be placed on them by the approach slab and the additional dead and live loads from the new superstructure. The footing was extended on each side of the abutment, four additional piles were driven, and the footing was extended at the abutment to resist lateral forces.

The substructure repairs and modifications included work on the approach spans, the resting piers, and the pivot pier, in addition to crack injections and spalling repairs. The plan called for removing the existing steel rocker bearings in the approach spans and replacing them with new isolation bearings made of neoprene rubber with a lead core. This solution called for steel shim packs between the bearing and the bottom flange of the new girders, as well as epoxy grout below the bearing to account for the height differential. The pivot pier modifications included repairs to a large hole in the top of the pivot pier cap created when Hurricane Hugo knocked the swing span off its pivot bearing. The pivot pier also underwent 600 linear ft of crack injections and 10 cu ft of spall repairs.

The resting pier modifications included furnishing and installing a new swing span lock assembly, which would serve as a wind shear key, as well as new end lifts that would align the swing span deck with the deck of the approach spans. The work also included adding hurricane tie-downs in the form of eyebolts anchored to the top of the pier cap and connected to the outer floor beams of the swing span. This work was meant to prevent a recurrence of the events seen in Hurricane Hugo.

THE NEW APPROACH SPANS' superstructure consists of four three-span, continuous steel plate girder units; the three spans, proceeding from north to south, measure 70, 86, and 70 ft. The girders are supported on rubber isolation bearings anchored to the existing concrete piers. These replacement spans use welded plate girders that are 5 ft 6 in. deep to support rolled steel floor beams (W 24 × 76) spaced 14 ft apart and rolled steel stringers (W 18 × 46) that are spaced midway between the main load-carrying girders. Brackets at each floor beam cantilever from the girders to support the outer 6 ft of the concrete deck. The framing is similar to that of the old bridge; however, a change was made to the connections of the stringers to the floor beams. Instead of connecting to the top flange of the floor beam, the stringers now frame into the floor beam webs with connection angles. This connection change prevents out-of-plane bending, which had caused cracks at the interface of the webs and flanges in the original stringers. To increase the bending strength, the steel framing members were designed to act compositely with the 8 in. reinforced-concrete deck. The approach spans' total weight is approximately 15 percent greater than in the original bridge, a result of the RFP requirement that the deck thickness be increased from 7 in. to 8 in. and of the additional roadway width and sidewalk.

The weight of the structural steel to be used in the new approach spans was similar to that in the existing bridge, but the live-load capacity was increased by using the lightweight concrete. In accordance with the 1940 AASHTO bridge design manual that was used, the original bridge was designed for a 20-ton truck in each lane of traffic. The new bridge has been designed for a 36-ton truck in each lane.

The bridge railings were designed to resist the expected loads and to match the appearance of the existing railing, which consists of steel pickets between the concrete posts. The concrete posts were designed to resist the entire load, a solution that was allowed by the RFP.

To determine the maximum stresses on the swing span, the span was analyzed in accordance with the AASHTO LRFD codes as a two-span continuous structure in the closed position and as a cantilevered structure for dead loads in the open position. Erection stresses also were calculated to account for the expected construction procedures, which called for a new swing span to be mounted on a barge that would float the span into place. For this procedure, the swing span was modeled as a simple span cantilevered at both ends. A three-dimensional SAP structural analysis model of the truss was created to assist in determining the maximum loads for each component of the truss.

The new swing span's superstructure is a Warren through truss modified to accommodate the center pivot. The appearance matches that of the original swing span, with the exception of the roadway widening, the addition of the new, wider sidewalk, and the vertical clearance of the portal, which comprises the end posts and bracing at the entrance to the truss structure. The portal was raised to a height of 16 ft. A midheight brace within the truss was provided to match the original swing span's appearance even though it was required structurally only at the portal.

All of the new steel components match the original as closely as practical while utilizing current steel design and fabrication techniques. The elevations of the bottom and top chords match those of the original truss chords to replicate the appearance of the original structure and ensure the correct navigational clearance. High-strength bolts were specified for all of the field- and shop-bolted connections to provide an appearance of riveted connections that would match the original structure. Given their improved resistance to corrosion, wide-flange rolled beams and H-shaped piles were used in place of latticed channel members.

An Exodermic deck system—manufactured by the D.S. Brown Company, of North Baltimore, Ohio—that uses lightweight concrete and steel grating minimized the swing span's weight by requiring fewer stringers than would have been the case with a concrete-filled grating system. The concrete deck was to be planed or ground to meet rideability requirements and grooved to improve skid resistance. Likewise, the sidewalk consists of aluminum grating panels and steel railings, and the railing system was made entirely of steel to minimize weight. An extensive bracing system beneath the sidewalk was required to meet the load resistance requirements.

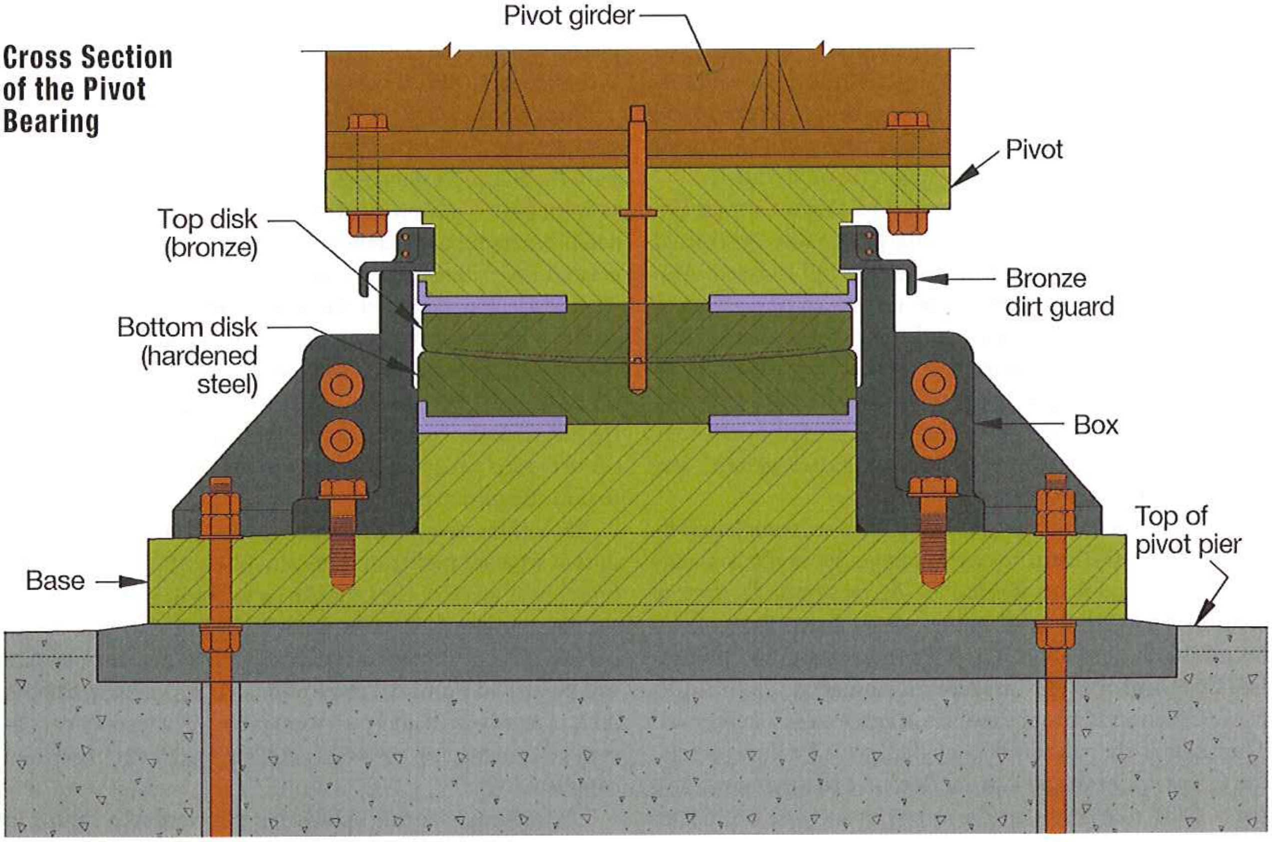
The control house is located above the roadway inside the trusses' sway bracing. Like the original, the new control house is octagonal but is slightly larger to offer improved views of the waterway and roadway for the bridgetender and to accommodate the new electrical equipment and a restroom.

The mechanical systems for the swing span include drive machinery, support machinery, and lock machinery. All of the mechanical systems and components were designed, fabricated, and erected in accordance with the AASHTO LRFD requirements cited above. PCL, Hardesty & Hanover, and Steward Machine Company, Inc., of Birmingham, Alabama—the project's machinery supplier and fabricator—drew on their experience to help design the details of the mechanical components.

The drive machinery consists of two independent drives, each capable of operating the swing span in the event of a motor failure in the other. The machinery is located on a platform on the swing span above the pivot pier but below the roadway deck. The platform spans between the pivot girder and a pinion girder on either side of the pivot. Each independent machinery system consists of a 10 hp motor that drives a closed reduction gearbox. An extended input shaft at each gearbox is accessible through the roadway deck; in the event of a power failure or loss of both motors, a capstan T bar has been provided to engage the extended shafts and make it possible to rotate the span manually.

The span support machinery consists of the center piv-

Cross Section of the Pivot Bearing



DRAWING BY K. SEXTON, HARDESY & HANOVER

ot bearing, eccentric end lifters, center rollers, and balance wheels. The center pivot bearing is a bronze and steel disk in an oil lubricant bath inside a steel box. The bearing supports the entire weight of the swing span in the open position in addition to lateral loads induced by the swing span during a seismic event (approximately 320 kips) and live loads from vehicular traffic in the closed position.

The end lifters were used instead of an end wedge system to minimize weight on the span and improve access for maintenance. The eccentric rollers, which are driven by an electric motor and a worm gear, are mounted to the floor beams at the ends for easy access. The eccentric rollers partially remove the dead-load deflection from the swing span in the open position so that the span can meet the approach elevation when it is closed. The function of the two center rollers is to resist live loads and vehicular impacts. Using center rollers instead of the more common center wedges eliminates the need for actuation machinery or electrical equipment. The only routine maintenance associated with this type of live-load support is the lubrication of the bearings.

In accordance with AASHTO specifications, eight balance wheels were provided to counter the overturning moments induced by wind loads during operation. A combination of shims at the connection with the superstructure and wheel bearings provided the proper clearance at installation and will facilitate future adjustments.

Swing spans have an advantage over the other two major movable bridge types, bascule and vertical lift, in that they are typically symmetrical about their axis of rotation. This symmetry provides balance without the use of the large counterweight required in bascule or vertical lift bridges. Although swing spans are inherently balanced, there can be some small imbalances, both longitudinally and transversely, caused by machinery, electrical equipment, roadway asymmetry, or specialized structural components. In this bridge, minor accommodations were necessary to account for the asymmetric roadway section resulting from the fact that the sidewalk is located on only one side of the bridge. To achieve balance, the concrete deck was made thicker on the east side of the roadway, and additional ballast was added beneath the sidewalk.

THE DESIGN AND CONSTRUCTION of the Ben Sawyer Bridge were keenly followed by local residents and mariners. Recognizing the value of experience and professionalism in public information and community outreach, the team worked with Civic Communications to mount an effective public information campaign. The community relations plan sought to meet the concerns of local residents, their related community organizations, and public leaders by sharing information through written materials as well as personal contacts. To ensure that information was accurate and was provided in a timely manner, the design/build team provided all of the necessary background and scheduling information. A project Web page was created on the SCDOT Web site so that community members could receive updates, follow the progress of the project, view traffic announcements, and provide feedback. The plan also included a construction community forum that enabled residents to ask questions about the construction process. The forum also served as a platform for announcing detours that would affect vehicular and marine traffic at least 48 hours in advance. As a supplement, periodic updates were sent directly to area politicians, news organizations, and interested community organizations; flyers that addressed particular issues regarding the scheduling of the project were produced and distributed; and speakers and presentation materials were made available to the SCDOT as needed for public presentations.

To adhere to permits issued by the U.S. Army Corps of Engineers and the U.S. Coast Guard, the bridge was constructed on the existing alignment with no shift in right-of-way. Also in accordance with the permits, no temporary or permanent fill was used in critical areas (wetlands); access trestles were provided to palliate the deleterious effects of construction on wetlands by allowing daily tidal inundation in the construction area; and any marsh areas that were affected by the trestles were returned to their original contours, revegetated, and monitored after construction.

The construction of the new swing span was completed off-site to reduce the harm to environmentally fragile wetlands on the north and south approaches. An erosion and sediment control plan was developed and submitted to the Town of Sullivan's Island, the City of Isle of Palms, and the South Carolina Department of Health and Environmental Control's Office of Ocean and Coastal Resource Management for approval. Throughout the project, PCL worked with local inspectors, the Office of Ocean and Coastal Resource Management, and the SCDOT to ensure that the sediment and erosion control procedures were maintained.

In keeping with the requirements set forth in the RFP, the bridge remained open to two lanes of vehicular traffic at all times during construction, with the exception of the permitted nighttime lane closures and the total bridge closure period.

The design/build team had a constructive working relationship with the Coast Guard and coordinated construction planning with it early in the project to ensure that the required closures of the navigable channel would not interrupt marine traffic. This coordination included regular submissions for review and comment by the Coast Guard of the construction sequence plans, mooring plans, and the project's critical path schedule. With the exception of the 10-day closure, marine traffic was maintained throughout construction, and when required, PCL submitted an application for closure 120 days prior to the event so that mariners could be alerted.

The new approach spans were prefabricated directly west of the existing structure on temporary bents and access trestles. After the erosion control systems were put in place and the embankments were cleared and grubbed, the east and west access trestle and temporary bents were installed simultaneously using top-down construction methods. Installation began at the abutment and progressed toward the rest pier as each trestle section was completed. This cycle continued until the complete access structure and all of the temporary approach bents were installed at each quadrant of the bridge.

The approach spans on either side were then erected concurrently to meet the scheduling requirements and closure restrictions. During the bridge closure, the existing approach spans were shifted east to temporary bents whose spacing mirrored that of the existing concrete piers, and the new spans were shifted east onto the existing concrete piers. Rollers were placed beneath the existing and new superstructures to assist as tension jacks pulled the spans into their proper positions.

Prior to shipment, all of the steel components of the approach were primed and coated in the shop in accordance with the SCDOT's standards. The north and south approaches were placed simultaneously beginning at the abutment and progressing toward the rest piers. The main girders were erected on grillages on the temporary bent header beams. This made it possible for the loads from the new approach spans to be transferred to rollers upon completion. A temporary jacking beam was then connected to the underside of the main girders to facilitate jacking and load transfer once the erection was completed. The grillages beneath the girders were used to connect the tension rods that were employed to pull the girders.

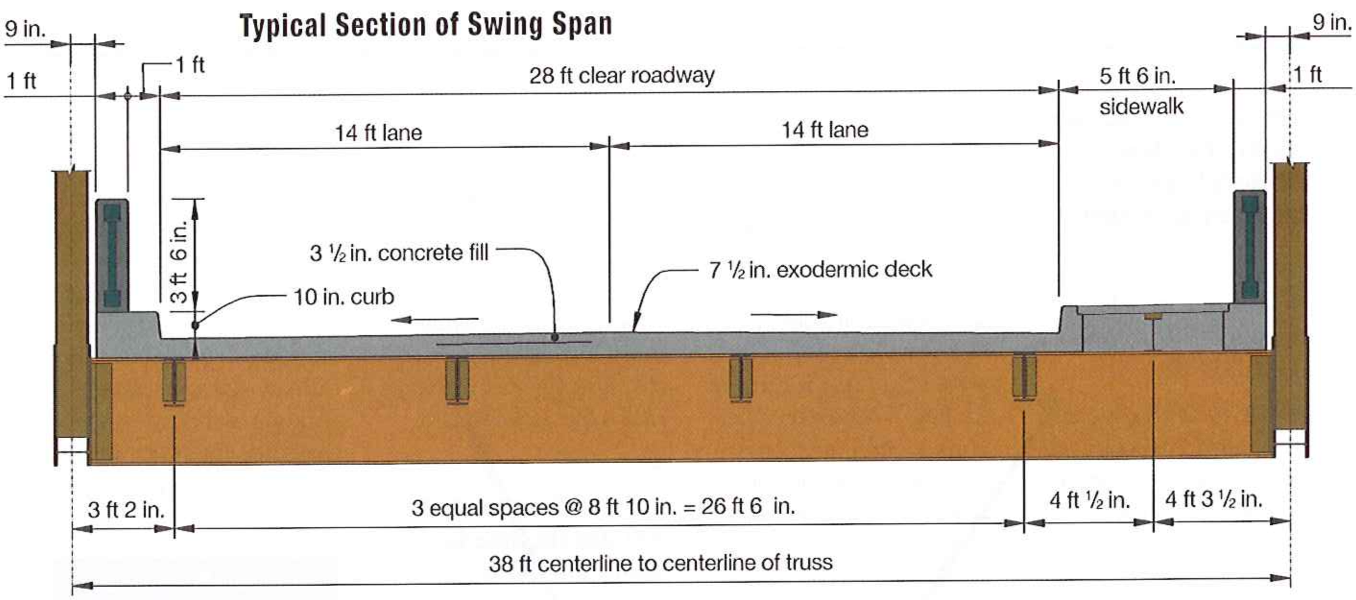
Each three-span continuous approach deck was placed in two separate nighttime concrete placements. As each approach was erected, the concrete crew began construction of the stay-in-place deck forms, followed by installation of the rebar and the replacement of the concrete. The final deck surface was planed and grooved to provide an exceptionally smooth deck. The sidewalk and curb were placed in a secondary concrete placement after construction of the bridge deck had been completed.

The new and existing approach spans were then shifted in two operations; the four existing units and the four new units were shifted in 4 in. increments in unison and rolled off of and onto their corresponding temporary bents and substructure using 50-ton tension jacks pulling the high-strength rods mentioned above.

A concerted effort was made to ensure that the spans were all pulled at the same rate, and this process was monitored to ensure that during the rolling operation the spans did not become misaligned or racked, that is, situated on a skew in such a way that the span would jam on its guides. The operation of moving the existing superstructure off the existing substructure and moving the new superstructure onto it took approximately 24 hours for each approach. After the spans were in place, the girders were jacked and fitted with new isolation bearings and grouted into place.

The new swing span, including the structural steel, the control house, the mechanical and electrical equipment, and the Exodermic deck grating, was erected off-site at a shop established at a staging yard at the Port of Charleston terminal. The close proximity of this terminal to the bridge site significantly reduced the risk associated with a long-distance barge trip. During the erection process the span was supported on temporary bents designed to ensure that the structure was not overstressed during the process. The components were temporarily bolted to minimize alignment issues during construction. PCL and Hardesty & Hanover coordinated their efforts with the team's quality control manager to ensure that all parties understood how work was to progress and that any concerns throughout the shop erection process were properly addressed.

An engineered floating scheme was designed to transfer the swing span and ensure that all temporary supports were


Typical Section of Swing Span

DRAWING BY K. SEXTON, HARDESY & HANOVER

correctly positioned. The PCL project manager coordinated all aspects of the swing span construction, the barge procedures, and the transfer of the existing and new swing spans.

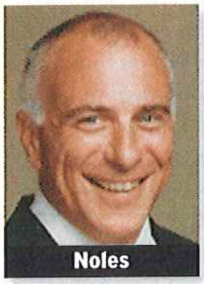
Prior to the closure of the bridge, the new swing span was transferred to a 50 by 180 ft barge at the Port of Charleston. The transfer was carried out in such a way as to ensure that the span would not be overstressed during the move. The barge had been outfitted with falsework that would enable the team to remove the existing swing span and place the new swing span on the existing pivot pier. The falsework was placed at an elevation that made it possible for the system to float under the old swing span at low tide and lift the span at high tide. To transfer the 700-ton swing span from the staging yard to the barge, a system of hydraulic pulling equipment and rollers similar to the system used to transfer the approach spans was used.

After the swing span was rolled onto the barge but before bridge closure, the span was floated to the bridge site and aligned adjacent to the original swing span. At that point the channel was closed to navigation, and the bridge was closed to vehicular traffic. The falsework mounted on the barge was positioned beneath the swing span, and in conjunction with the hydraulic jacks, it lifted the span with the rising tide. After the original swing span was transferred from the pivot pier to the barge, the barge turned 180 degrees so that the new swing span would be aligned with the new approach spans.

Before the new swing span could be placed, work had to be done on the rest piers and pivot pier. Concrete modifications were required because the new bearing was larger than the original. Furthermore, the span drive machinery's track and rack system overlapped with the original and therefore could not be replaced until the closure. Anchor bolt holes were drilled using templates made from the machinery components that were to be placed on the pier. The new span's lock receivers were set on the rest piers but were not permanently mounted until the new swing span was set. This ensured that the guide and the receiver would be properly aligned.

Upon completion of these modifications, the barge with the new span moved so that the span was above the pivot pier, and with the receding tide the span was placed on the pivot bearing. Once the new span was set, the rack segments were shimmed and aligned with the pinions. After the final alignment of the pivot bearing, rack, track, span locks, and end lifters, the components were grouted in place. The span was then manually rotated using the capstans so that marine traffic could pass through the channel. Next the span's electrical system was tested. With minor tweaks to the system, the span operated flawlessly.

After a total of 260 hours, during which the engineers and constructors, working 12-hour shifts, experienced rain, wind, snow, and freezing temperatures, the bridge was opened to traffic on February 19, 2010, at 1:50 AM. This was almost one day more than the required closure time but still represented a herculean effort given the circumstances, especially the effect that the cold temperatures had on the curing time of the grout and the fact that the wind delayed the barge for more than two days. The mayor of Sullivan's Island, Carl Smith, was the first to cross the new superstructure, making the trip in a 1928 Model A Ford. The community now has a modern swing bridge that marries the beauty of the original with the smooth operation of a contemporary facility. **CE**


Noles

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PROJECT CREDITS **Owner:** South Carolina Department of Transportation **Engineer of record:** Hardesty & Hanover, LLP, Sunrise, Florida **Geotechnical consultant:** SM&E, Inc., Columbia, South Carolina **Civil engineer:** Florence & Hutcheson, Columbia, South Carolina **Construction firm:** PCL Civil Constructors, Inc., Tampa, Florida **Construction manager:** Columbia, South Carolina, office of Parsons Brinckerhoff **Machinery supplier and fabricator:** Steward Machine Company, Inc., Birmingham, Alabama