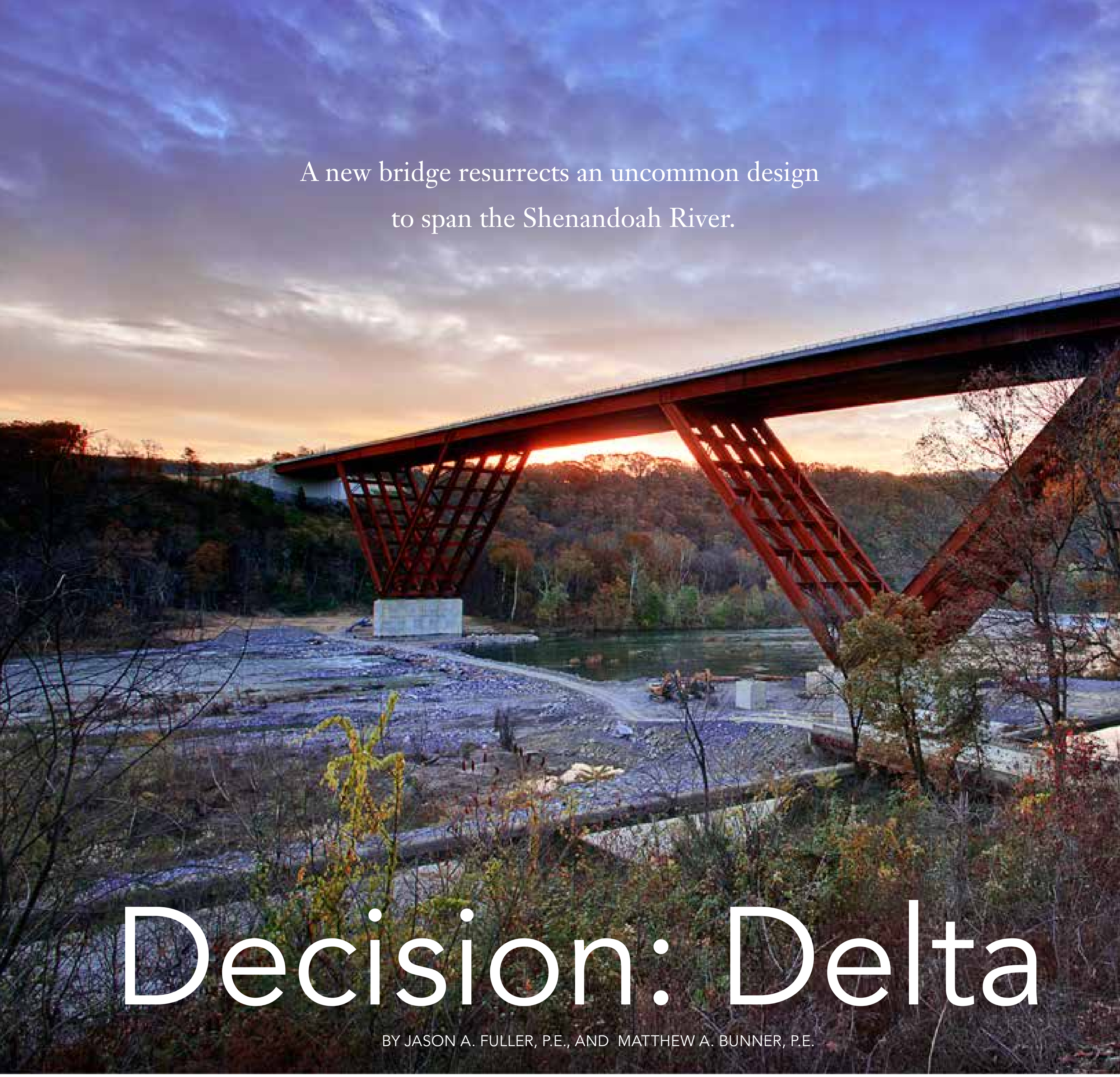

A new bridge resurrects an uncommon design to span the Shenandoah River.

Decision: Delta

BY JASON A. FULLER, P.E., AND MATTHEW A. BUNNER, P.E.

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JUST AN HOUR'S DRIVE west from Washington, D.C., the new Shenandoah River Bridge stands in aesthetic harmony with its surroundings.

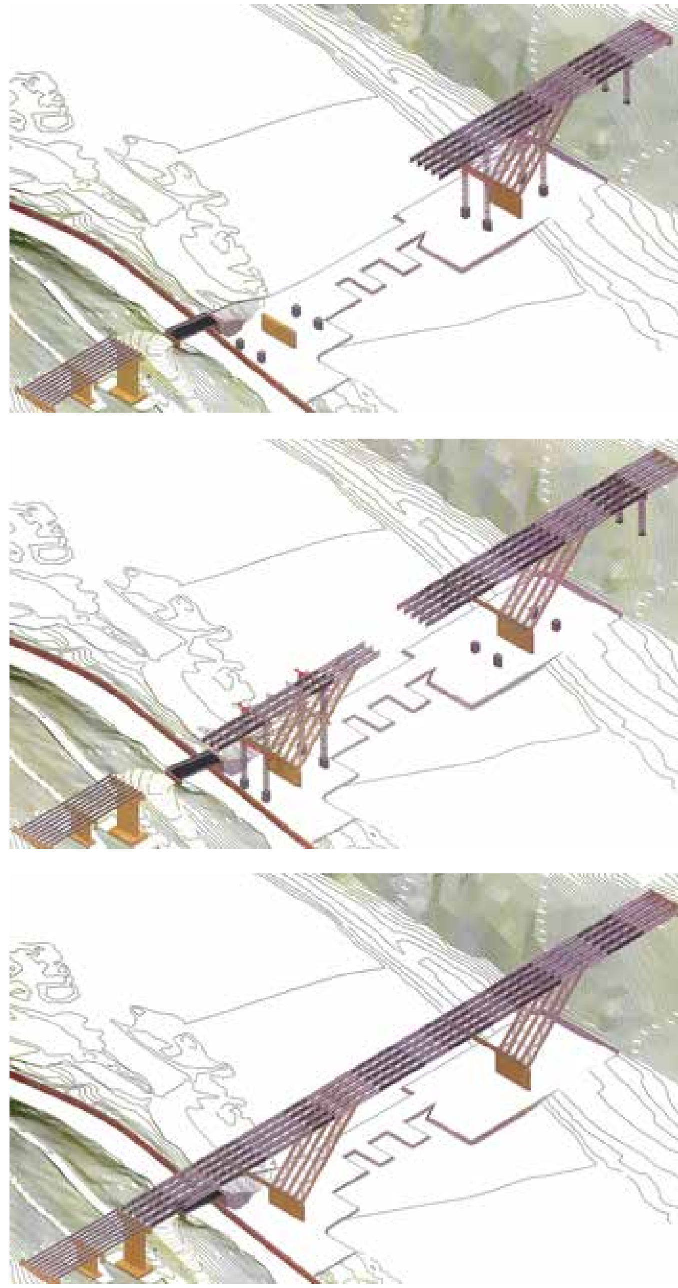
The project exists within a unique ecosystem where the scenic Shenandoah River valley boasts steeply rising wooded mountains, a diverse wildlife habitat, rolling farmland and quaint, historic towns. Not surprisingly, the region has evolved into a desirable getaway from the frenzy of urban life.

With the subsequent increase in traffic, the West Virginia Department of Transportation—Division of Highways

Photos: Courtesy of HDR, Keith Philpott, photographer

◄ The Shenandoah River Bridge uses 6,325 tons of structural steel.

▼ Various stages of the steel erection.



(WVDOT) determined that the winding two-lane road that carried West Virginia Route 9 (WV9) through the valley was no longer sufficient. In September 2009, it revealed the design for a new alignment: a four-lane divided highway using a bridge over the Shenandoah River. At the crossing location, the proposed grade was nearly 200 ft above the river, and the overall bridge length would be nearly 1,800 ft. While there are no navigation requirements for the river, the environmental constraints for the project and the relatively high cost of substructure units located in the valley dictated that the main span be approximately 600 ft in length. To accommodate these constraints, a three-span continuous deck truss configuration (400 ft – 600 ft – 400 ft) with short plate-girder approach units was initially selected during the design phase.

In early October 2009, WVDOT modified the procurement from design-bid-build to design-build and instructed contractors that they could bid the as-designed truss or develop and bid a different structure type, providing they addressed the following criteria:

- The chosen substructure locations for the deck truss bridge generally must be used, with very limited latitude.
- The established horizontal and vertical alignment could not be changed.
- Alternatives that required increased amounts of disturbance to the gorge slopes would not be considered.
- The use of a causeway or cofferdams, other than as shown on the plans for the as-designed bridge and/or in the Section 404 (of the Clean Water Act) Permit, would require re-permitting.
- The design must comply with all previously established environmental commitments.

The superstructure consists of a five-girder, four-substringer system supported by five lines of delta legs—one for each girder.

Following concept approval, structural engineer HDR Engineering developed a delta frame design that delivered significant savings compared to proposals for more traditional designs and also resurrected a tried-and-true form that had been largely forgotten since the 1970s.

A New Look at an Old Design

HDR and general contractor Trumbull Corporation performed preliminary design and pricing on both concrete and steel options, and found that the anticipated construction costs for the concrete option were much greater; further evaluation focused solely on the steel alternatives. It was understood that deck configuration and cost would be similar for all of the proposed bridge schemes; therefore, the difference in cost would primarily be driven by the amount of steel, unit cost of fabrication and erection cost.

Based on a database of past projects, the team believed that a steel plate girder option with span lengths similar to the originally proposed truss configuration (400 ft – 600 ft – 400 ft) would result in approximately 145 lb. per sq. ft (psf) of structural steel, or approximately 50% more steel than the truss configuration, which would have been around 100 psf. From a superstructure perspective, the overall length of the delta frame unit would have been ideal for a traditional five-span steel plate girder unit with span lengths of 250 ft – 300 ft – 300 ft – 300 ft – 250 ft. Such a scheme would likely result in only 60 psf of structural steel; however, the design constraints did not allow for additional piers.

While investigating the possible plate-girder arrangements, the team determined that the ideal five-span plate girder option actually could be achieved if supports for the girders were provided 150 ft to either side of the as-designed river pier locations. The supports, envisioned to be steel slant legs at each girder line, could be inclined and meet at the existing river pier locations. With 200 ft of vertical space from the profile grade to the river, the supports could be inclined as much as 45° and still remain above the required river flood elevation (there was no requirement for navigational clearance).

The delta frame design produced 110 psf of structural steel, which was slightly above the original truss weight but facilitated significant fabrication cost savings (the structural steel cost was only about $1.65/lb including erection, which was approximately $0.75/lb less expensive than what was anticipated for the truss). These fabrication cost savings, along with other cost-effective options, offered a total savings of about $8 million (20%) compared to the next low bidder, and more than $13.5 million (33%) when compared to the two bidders that proposed a segmental concrete option.

The final steel superstructure of the new bridge consists of a five-girder, four-substringer system supported by five lines of delta legs—one for each girder. Each individual leg covers a vertical distance of 150 ft and a horizontal distance of 150 ft, creating a girder span of 300 ft between the delta legs. The span lengths between the abutments and piers adhere to the original configuration: 400 ft – 600 ft – 400 ft.

Relatively few rigid steel frames of this type have been constructed over the past few decades, and the singular nature of the bridge design meant there were no directly applicable design codes for portions of the structure. In some cases, such as in the design of the slant legs, the team had to establish design criteria and perform tailored design checks based on an interpretation of the code provisions and the use of other technical research that was available.

Putting it All Together

The Shenandoah River Bridge's distinctive design demanded unique procedures for erecting the legs and tall temporary

Pre-deck...

...and post-deck.

works and to accommodate the small site footprint, fluctuating river levels and other challenging site conditions. Modeling and analysis of the staged bridge erection developed as an extension of the final design. The team modified the non-composite detailed model used for analyzing the completely assembled steel framing to perform the staged erection analysis. Falsework towers, tensioned stays and temporary supports were added to the model. All elements of the modular truss falsework tower sections were included in the model as beam elements to facilitate design of the tower elements for all global and local effects. Stays were modeled as tension-only cable elements, and springs were used to model the connection (jacks) of cross girders to structural steel girders or legs. The vertical connection of the cross girder to structural steel was modeled with compression-only springs.

The project team implemented a geometric nonlinear analysis to evaluate the structure, including falsework, piece-by-piece with load tracking. The structure was modeled in 77 stages, where a stage is defined as the amount of work that could be completed during a shift or between any appreciable wind or thermal event. Each stage was then separated into individual steps. A new step was specified each time the lifting crane was released and a new piece was placed. A total of 207 individual steps were further defined in the model.

Many of the benefits of the delta frame scheme were realized not during design but rather during construction. For example, a completed delta frame (two legs and girder between) for one or more girder lines provided a significant amount of bracing to the temporary towers. After closing a delta frame, the structural steel also transferred a large portion of dead, wind and thermal loads during construction to the supports. Even prior to the formation of a delta, attaching multiple lower leg pieces to the falsework cross girder and lower knuckle (and river pier) provided significant rigidity to the temporary structural system. The participation of the structural steel as a temporary support helped reduce the size of temporary works and created a stable, stiff system prior to completion.

Additionally, due to structure symmetry about both the longitudinal and the transverse centerlines, four similar quadrants were built. With each section that went up, including temporary works, the crew gained experience that improved production rates for subsequent sections.

Natural Challenges

As majestic as the Shenandoah River valley is, the topography of the bridge's location posed significant site access and staging restrictions. An access road with multiple switchbacks, a temporary bridge to span a hydroelectric raceway and a causeway spanning the full width of the river, with pipes to accommodate flow, were all required, and steel had to be delivered on demand to accommodate the lack of on-site storage capacity.

Nature itself presented more than its fair share of challenges, as well. During the early stages of erection, in August 2011, a 5.8 magnitude earthquake occurred less than 100 miles from the site. Between 2010 and 2011, the Shenandoah River also experienced four of the top 50 highest watermarks of the last 140 years. Winds exceeding 50 mph were commonly seen during thunderstorms, and the occasional hurricane brought gusts exceeding 70 mph. Through all of these challenges, the temporary works and partially completed bridge proved to be sound.

The team delivered the new Shenandoah River Bridge on time and within the original design budget. Construction began in late 2010, with steel erection from September 2011 to August 2012, and was completed and opened to traffic in November 2012. WVDOT's willingness to use the design-build process—and consider and embrace the delta frame design—was para-

▲ The four-lane bridge is part of a new alignment for WV9, which formerly accessed the valley via a winding, two-lane road.

▲ The structure was modeled in 77 stages, each defined as the amount of work that could be completed during a shift or between any appreciable wind or thermal event.

mount to the project's success. The bridge demonstrates steel's ability to not only be competitive, but notably more efficient and cost-effective in a span range that many believed wasn't possible in today's market. By taking advantage of all of the benefits of a structural steel package, this significant structure, which used 6,325 tons of weathering steel, was delivered at a relatively modest (for bridges with a 600-ft main span) $285-per-sq.-ft price tag, including design and construction inspection costs—and provides a crossing worthy of its spectacular surroundings. MSC

Owner
West Virginia Department of Transportation – Division of Highways

General Contractor
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Structural Engineer
HDR Engineering, Weirton, W.V.

Steel Detailer
Tensor Engineering, Indian Harbour Beach, Fla.
(AISC Member/NSBA Member)