PROJECT

Designing for Resilience and Durability on the Longest Spliced Precast Concrete Girder Bridge in Vermont

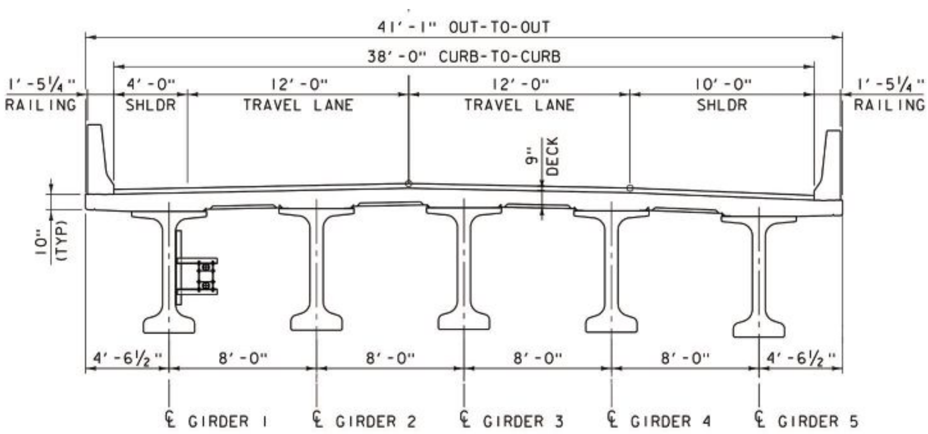
by Thomas French, HDR

Interstate 91 (I-91) carries travelers north and south along the scenic banks of the Connecticut River through the "Green Mountain State" of Vermont, from Massachusetts to the Canadian border. Amid the beautiful rolling hills in the southeast portion of the state, the highway crosses a moderate ravine in the town of Rockingham that contains the Green Mountain Railroad and the Williams River.

As part of the interstate highway expansion in the 1960s, the Williams River was relocated to its current location and causeways were constructed north and south of the river. Between 1963 and 1965, twin four-span steel deck-truss bridges were constructed to connect these causeways. The bridges, each nearly 750 ft long, independently carry traffic north and south.

As traffic levels increased over the years, portions of the concrete decks, concrete substructures, and painted steel truss superstructures began to show advanced levels of deterioration. Due to cold New England winters, I-91 is subjected to deicing agents for about six months of every year. At 50 years of service, the bridges exhibited reinforcing steel corrosion in the decks and columns and associated concrete spalling that required regular repair efforts beyond routine maintenance. The Vermont Agency of Transportation (VTrans) undertook an alternatives analysis and determined that a bridge replacement project was warranted.

Citing overall project schedule reduction and the desire for an innovative solution, VTrans opted for a design-build project delivery method. During the bidding period, the design-build team evaluated several alternative structure types, including balanced-cantilever segmental concrete box girders, steel haunched girders, and precast concrete girders. The design-build team ultimately selected precast concrete spliced-girder bridges due to overall project cost, construction methods that matched the contractor's skill set, relative ease of construction, a structure type that exceeded the 100-year service life requirement of the bridges, and the availability of a relatively local precaster that could supply the necessary components of the bridge.



Cross section of the new northbound bridge in a constant-depth section. The southbound bridge has the same cross-sectional dimensions. All Photos and Figures: HDR.

To provide the best solution to achieve the project goals, identical twin structures were constructed in place of the existing bridges. To match the interstate highway corridor, each bridge now provides two 12-ft-wide travel lanes, one 10-ft-wide breakdown shoulder, and one 4-ft-wide median shoulder. Each new bridge is over 41 ft wide, more than 6 ft wider than the existing bridges.

Project Requirements and Local Challenges

The request for proposals for the design-build project included several important criteria to ensure the replacement bridges

profile

INTERSTATE 91 BRIDGES 24N AND 24S / ROCKINGHAM, VERMONT

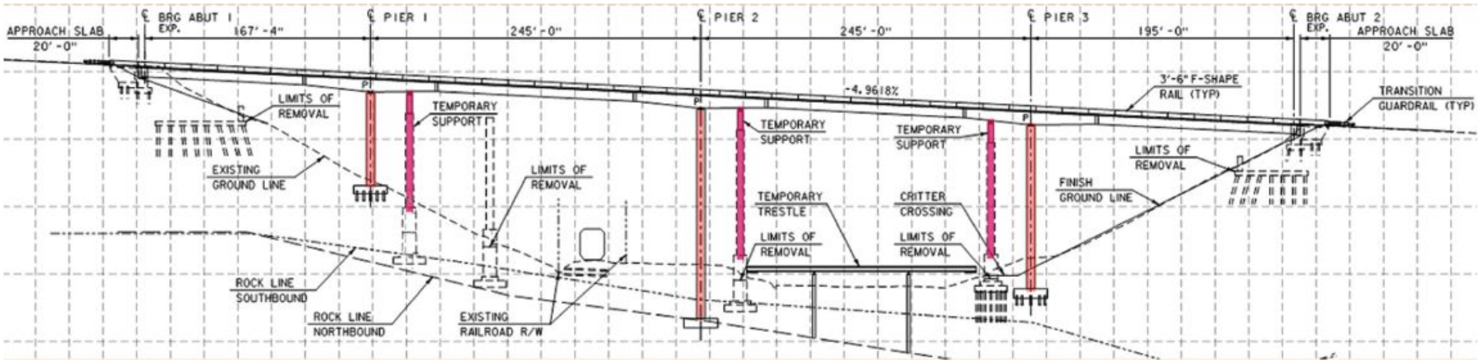
BRIDGE DESIGN ENGINEER: HDR, Omaha, Neb.

ERECTION ENGINEER: McNary Bergeron & Associates, Tampa, Fla.

PRIME CONTRACTOR: Reed & Reed Inc., Woolwich, Maine

PRECASTER: J. P. Carrara & Sons Inc., Middlebury, Vt.—a PCI-certified producer

POST-TENSIONING CONTRACTOR: DYWIDAG-Systems International USA Inc., Bolingbrook, Ill.



Elevation view of the new bridges showing temporary girder support locations and the temporary work platform.

would meet the needs of VTrans and the traveling public throughout the structures' service lives.

Span Configuration

The bridge concept could include any span configuration, as long as piers did not impede the riverbanks more than the existing bridge, or encroach on the railroad right-of-way envelope. To accomplish this, the design-build team proposed a four-span structure with identical 245-ft-long main spans and unsymmetrical end spans with lengths of 167 ft 4 in. and 195 ft, respectively, resulting in a completed bridge length, including closure pours, of just over 860 ft. The proposed bridge was 110 ft longer than the existing bridge as a result of eliminating two 45-ft-long vaulted abutments and constructing the new abutments behind the existing abutments to avoid pile conflicts. This particular span layout allowed the contractor to use the existing piers 2 and 3 as temporary supports during girder erection.

Hundred-Year Life Expectancy

The structures must have a life expectancy without a significant rehabilitation event for a minimum of 100 years. The design team developed conceptual design details for each major component of the bridges, and those details were evaluated by corrosion specialists to determine the time to initial corrosion period and the propagation period, the sum of which result in the time to first repair. The team balanced concrete cover and mixture proportions with appropriate reinforcing material types to achieve major bridge elements that met the required life expectancy in an aggressive deicing environment. **Table 1** lists the major bridge elements and their respective requirements for concrete design strength, reinforcing bar material type, concrete cover, and requirements for corrosion-inhibitor admixture.

Pier Slenderness Ratio

Understanding that the replacement bridges would have very tall piers, VTrans wanted to ensure resiliency by limiting the pier slenderness ratio, kL/r, to no greater than 80, where k is the effective length factor, L is the unsupported length (height), and r is the radius of gyration. The intent of the slenderness ratio limit was to create a less flexible pier system with a lower susceptibility to cracking, thus increasing resiliency. To maintain a competitive bid price for the project, the design-build team needed to use pier forms that the contractor already had. This requirement locked in the cross-sectional shape of the piers. With the height of the piers set to match site constraints, and the radius of gyration

Table 1. Major bridge element criteria to meet 100-year service life requirements. Black bar was used for portions of elements not listed.

	Structural element	Design concrete strength, psi	Mild reinforcement material	Concrete cover, in.	Calcium nitrite corrosion-inhibitor admixture
Superstructure	Precast concrete girder	9000	Black bar*	1.75	Yes
	Precast girder, stirrups	9000	Stainless steel†	1.00	No
	Barrier (inside face)	4000	Stainless steel†	1.50	No
	Deck slab (top)	4000	Stainless steel†	2.50	No
	Approach slab (top)	3500	Epoxy-coated‡	2.50	Yes
	Girder splice CIP closure	9000	Black bar*	1.75	Yes
Substructure	Pier footings	3500	Black bar*	3.00	Yes
	Pier shaft	3500	Black bar*	5.50	Yes
	Pier cap	3500	Stainless steel†	4.00	No
	Abutment stems exposed face	3500	Black bar*	3.00	Yes

*AASHTO M 31M/M 31: *Standard Specification for Deformed and Plain Carbon and Low-Alloy Steel Bars for Concrete Reinforcement.*

†ASTM A955/A955M: *Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement.*

‡ASTM A775/A775M: *Standard Specification for Epoxy-Coated Steel Reinforcing Bars.*

VERMONT AGENCY OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: Twin 863-ft-long, four-span post-tensioned precast concrete spliced-girder bridges

STRUCTURAL COMPONENTS: Seventy modified NEBT-79 precast, prestressed concrete girder segments, 30 of which were haunched to 10 ft deep; 9-in.-thick cast-in-place concrete deck with stainless steel reinforcement and galvanized stay-in-place deck forms; cast-in-place concrete pier caps, columns, footings, and abutments on steel H-piles

BRIDGE CONSTRUCTION COST: $50 million

AWARDS: PCI 2021 Design Award, Best Bridge with a Main Span More Than 150 Feet

A haunched girder segment after being lifted off the delivery vehicle parked on the existing truss bridge. An in-depth analysis of the existing bridge demonstrated that it was safe to have the new girder segments on the existing structure as long as there was no other traffic on the bridge at the same time.

Piers for the northbound bridge during construction. To maintain a competitive bid price, the design-build team used pier forms the contractor already had.

and the height set by the cross section, the only variable the design team could work with was the effective length factor. Understanding that a traditional single bearing per girder would yield an effective length factor of 2.0 due to the transitional and rotational freedom that occurs in that configuration, the design team proposed an innovative two-bearing-per-girder design. This design resulted in rotational resistance at the top of the pier based on the relative stiffness between columns and girders that resulted in an effective length factor less than 2.0.

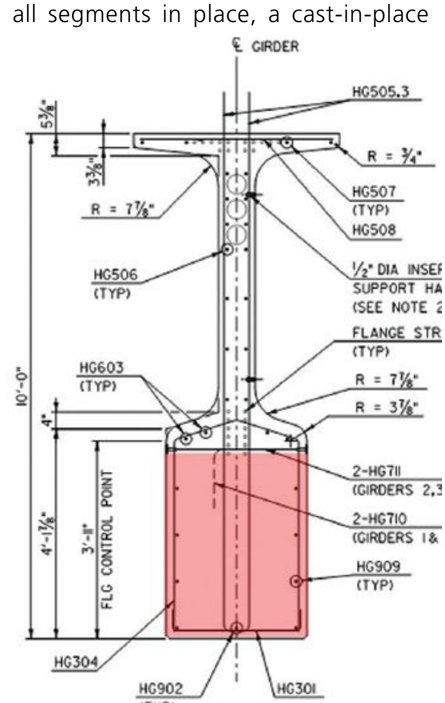
Constructing the Longest Spliced Precast Concrete Girder Bridge in Vermont

To span the ravine with four spans, each of the five girder lines comprises seven precast, prestressed concrete Northeast bulb-tee (NEBT) girder segments. Segments 2, 4, and 6 are identical and are haunched to sit on the piers. To construct the haunched girder segments, the precaster started with a standard NEBT-79 form but excluded the bottom form. The precaster custom made two variable-depth bottom forms to transition the bottom flange height from the standard 8.7 in. to 49.9 in. to provide the desired haunched depth. Each haunched segment weighs 93.5 tons (187,000 lb), is 96 ft long, and varies in depth from 10 ft at the pier to 6 ft 6¾ in. at the ends. Segments 1, 3, 5, and 7 are all 6 ft 6¾ in. deep and are 120 ft, 145 ft, 145 ft, and 147 ft 4 in. long, respectively, with the longest segment weighing 88.3 tons (176,600 lb).

The girder segments were fabricated only 96 miles away in Middlebury, Vt., but, due to site constraints, they had to be taken off the delivery vehicle from the existing bridge. An in-depth analysis of the aged existing bridge was performed, and it was deemed safe to have the new girder segments on the existing structure as long as there was no other traffic on the bridge at the same time. The contractor deployed a rolling roadblock that slowed highway traffic down, allowing for a 20-minute window in which to hook up a girder segment to a crane and lift it from the delivery vehicle.

The segments were erected by first placing the haunched girder segments over the piers. Before delivery to the site, each segment was fitted with two 24 × 24 in. reinforced elastomeric bearing pads. The segments were then lifted over their respective piers and placed on temporary supports that left an approximately 1 in. space below the bearings. The segments were surveyed, and the proper profile was set by adjusting the temporary support jacks. Once the segments were in the correct location and profile, high-strength nonshrink grout was placed to create the permanent plinth under the bearing pads. This procedure was undertaken to maximize bearing installation flexibility because the tolerance of bearing elevation pedestals was less than 1⁄16 in. By leaving the bearings floating while alignment adjustments were made, the bearings could be set without introducing any permanent rotational displacements.

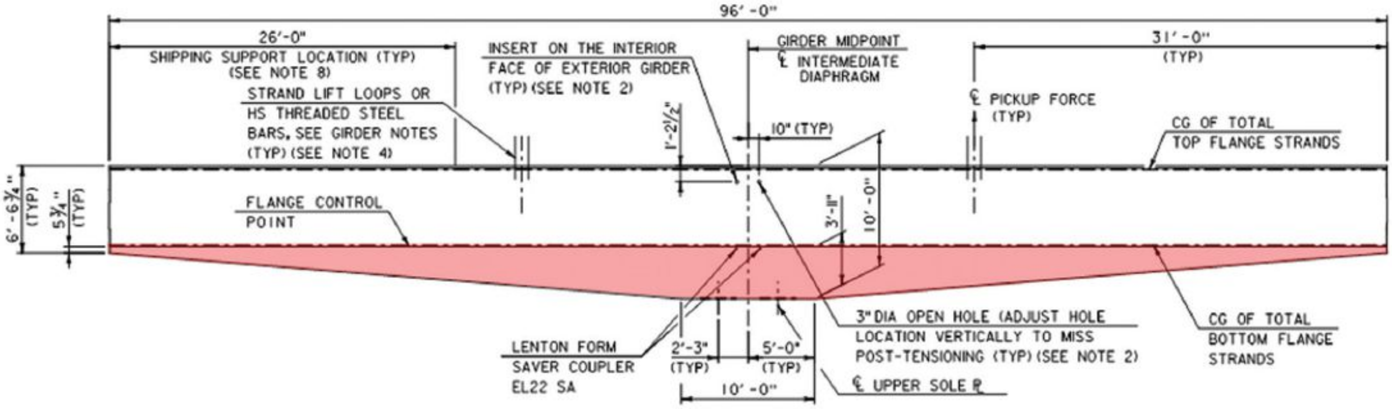
After the haunched girder segments were installed, the drop-in and end girder segments were added systematically and temporarily hung from the haunched segments using temporary steel strongbacks. With all segments in place, a cast-in-place



Cross section of haunched Northeast bulb-tee girder segment at the pier. Concrete section added to achieve haunch is shaded.

Table 2. Pier slenderness ratio for design

	Pier 1	Pier 2	Pier 3
Effective length factor *k*	1.900	1.177	1.265
Height of column *L*	86.4 ft	128.1 ft	117.5 ft
Radius of gyration *r*	27.7 in.	27.7 in.	27.7 in.
Slenderness ratio *kL*/*r*	71.12	65.24	64.37



Elevation view of the haunched Northeast bulb-tee pier segment. Each haunched girder segment varied in depth from 10 ft at the pier to 6 ft 6¾ in. at the ends and weighed 93.5 tons (187,000 lb). Concrete section added to achieve haunch is shaded.

closure diaphragm was constructed from exterior girder to exterior girder at each segment joint. After all of the diaphragms were cast and the concrete cured, each of the girder lines was post-tensioned with three bonded tendons containing nineteen 0.6-in.-diameter low-relaxation strands. The girders were post-tensioned from each end of the bridges, resulting in a 2079 kip total tensioning force in each girder.

Conclusion

Using the first precast concrete spliced-girder bridges in Vermont, the project's design provided an economical solution for this important transportation link. Key to that design is an all-concrete structure that incorporates pretensioning, post-tensioning, and a blend of reinforcing materials, allowing local suppliers to provide the necessary materials to ensure the required 100-year service life. The northbound bridge opened to traffic in April 2019 and the southbound bridge was expected to open in June 2021.

Thomas French is a senior project manager with HDR in Manchester, N.H.

Construction of the southbound bridge superstructure with the completed northbound bridge in the background.

AESTHETICS **COMMENTARY**

by Frederick Gottemoeller

Attractive bridges use their shapes to illustrate how they work: they are thick where the forces are the greatest, and thin everywhere else. People can intuitively understand the reasons for their shapes, and this understanding results in a positive feeling of engagement and satisfaction.

Because the efficient use of materials is an engineering criterion that encourages the use of such shapes, in theory it ought to be easy for engineers to produce attractive bridges. Unfortunately, engineering economy often gets in the way. Standardized shapes or bridge elements are less expensive because they are easier to produce, not because they embody the most efficient use of materials. Thankfully, engineering efficiency and engineering economy all came together in the Rockingham, Vt., Interstate 91 bridge project, and the result is structures that are efficient, economical, and elegant.

Let's start with the piers. Design requirements for a stiff pier plus the contractor's prior ownership of the forms encouraged a simple, tapered shape with an elegantly proportioned cap. Simplicity is underrated as an aesthetic characteristic, and this pier is about as simple as it can be. It's thickest at the bottom, where the overturning moments are the greatest; it gradually narrows toward the top, as the forces decrease; and then it widens to accept the girders.

The girder is thickened over the pier, which, in addition to accommodating the forces concentrated there, matches the intuitive understanding that there are forces concentrated there. The thickening is accomplished by the simplest method possible: tapering the bottom flange of the girder.

That's it. No other rustications or embellishments are present. No other rustications or embellishments are needed. Yet Vermonters will be able to take pride in these bridges for 100 years to come.

Rendering of the precast concrete spliced-girder bridges in Rockingham, Vt.