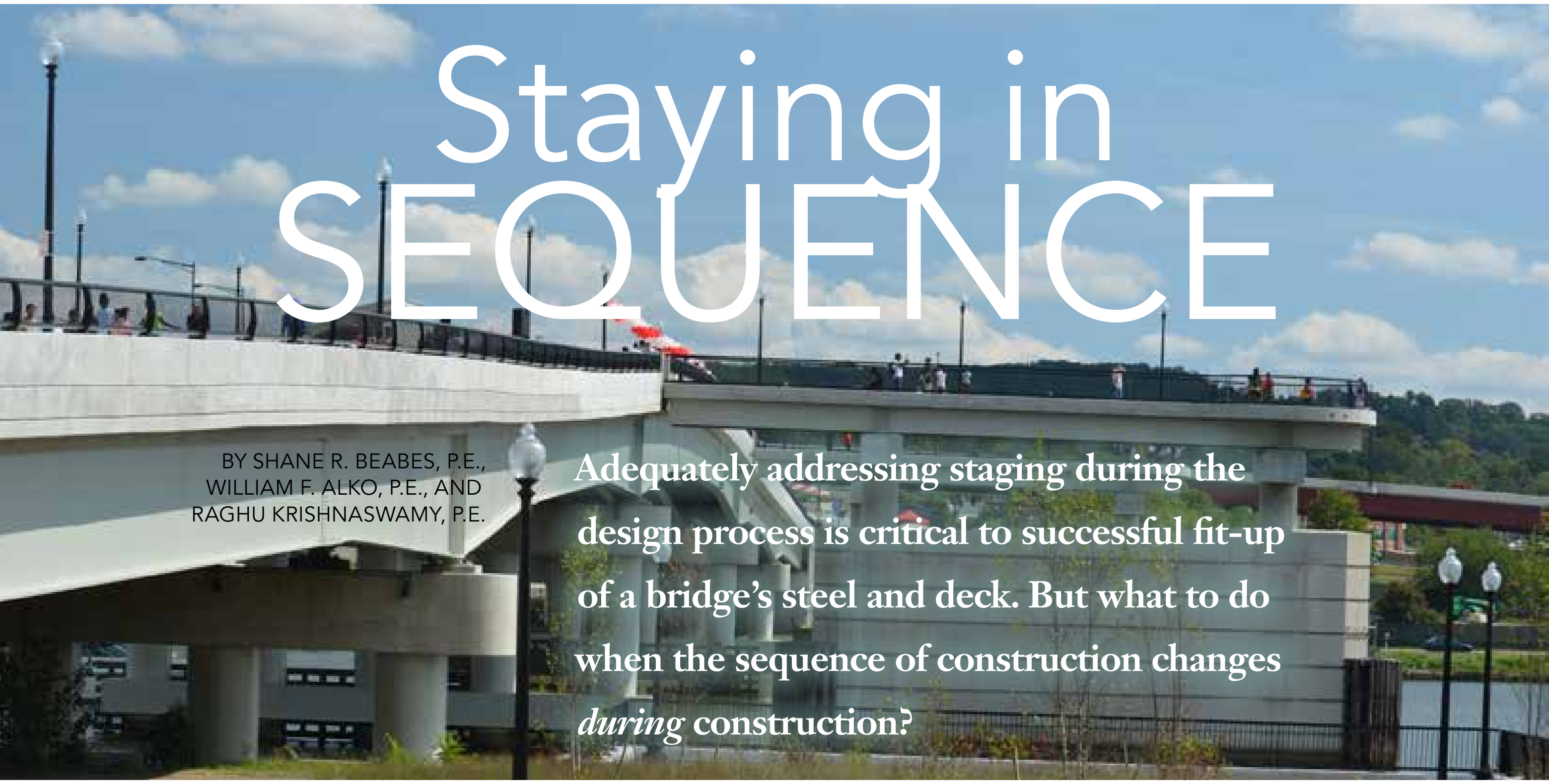

Staying in SEQUENCE

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Adequately addressing staging during the design process is critical to successful fit-up of a bridge's steel and deck. But what to do when the sequence of construction changes *during* construction?

SEQUENCING MATTERS.

Whether it is shored or un-shored, non-composite or composite or single or multi-stage construction, all of these techniques represent a sequence of construction for bridges that must be recognized by the engineer during the analysis and design process.

Considering the sequence of construction is critical to the methodology of load application, distribution of forces and prediction of deflections for the bridge structural framing system. In bridges that are tangent or mildly skewed, a line girder analysis (1D) is typically used to predict forces and deflections in a bridge system. Although not complex, the model's ability to best predict the performance of the girders will depend on the development and application of loads to the individual girders that are compatible with the staged sequence of construction.

For bridges that are curved or significantly skewed, a more rigorous analysis is often warranted. Typically, this will involve a 2D or 3D model. In these models, similar to the line-girder model, the application of load will depend on the staged sequence of construction. However, since the more rigorous models rely on the cross frames to distribute both dead load and live load forces to adjacent girders in the system, staged construction will dictate which girders are connected by cross frames at any given time, and ultimately the distribution of forces within the structural framing. Regardless of how simple or complex, the engineer must consider the sequence of construction to successfully predict the performance of the bridge.

Across the Anacostia

On the complex end of the spectrum is the 11th Street Bridge in Washington, D.C., part of an overall design-build-to-budget project let by the District Department of Transportation. The project was awarded based on a $260 million best-value, design-build, procurement process and involved the construction of three main river bridges and extensive ramp reconfigurations on both sides of the Anacostia River. The project included two new parallel Interstate bridges and one new local bridge, the 11th Street Bridge, with the objective of separating the Interstate movements from the local traffic, pedestrians and bicyclists.

The 11th Street Bridge is a 916 ft-long, five-span continuous steel I-girder bridge. Using 1,663 tons of steel (1,446 tons for fabricated I-girders and 217 tons for cross frames), it has spans of 170 ft, 170 ft, 234 ft, 171 ft and 171 ft; the longest span is located over the navigable channel. The superstructure framing includes sections of splayed, kinked, skewed and horizontally curved girders. To comply with project aesthetic requirements, the girder webs linearly vary in depth from approximately 76 in. within the positive moment regions to 108 in. within the negative moment regions, transitioning from the bolted field splices to the piers. The cross frames are inverted K-frames with a top chord, and the members are shop welded to the gusset plates and field bolted to the connection plates. The cross frames vary in spacing from 19 ft to 25 ft, are contiguous between bays, and are oriented perpendicular to the girders. The bearings are high-load, multi-rotational (HLMR) using a combination of non-guided expansion, guided expansion and fixed types. The substructures are oriented at 90° to the construction baseline.

Each girder line in the framing plan includes nine field sections and eight bolted field splices (FS) located near the dead load inflection points; the field splices are numbered sequentially from FS1 to FS8. Girder lines (G) are numbered from G1 to G7 (see plan on following page).

The girder spacing varies from 10 ft to nearly 13 ft to accommodate the flared geometry at each end of the bridge, and

Stage 2 framing and closure bay with an upward load on G1 (jack stand) and downward load on G1 (concrete block).

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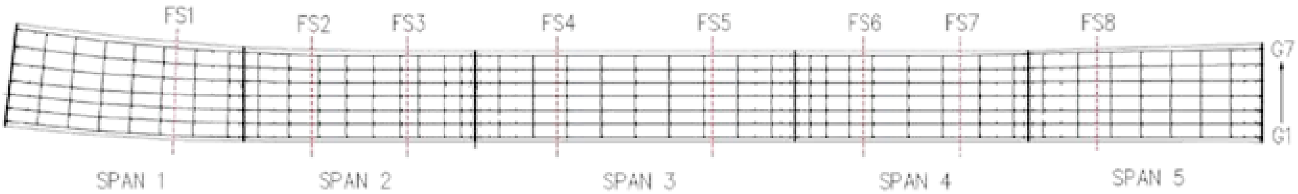
A conflict between the existing bridge (left) and proposed bridge (right); notice the discontinuous girder lines (G1 and G2) on the proposed bridge.

Girder spacing varies from 10 ft to nearly 13 ft to accommodate the flared geometry at each end of the bridge.

The framing plan.



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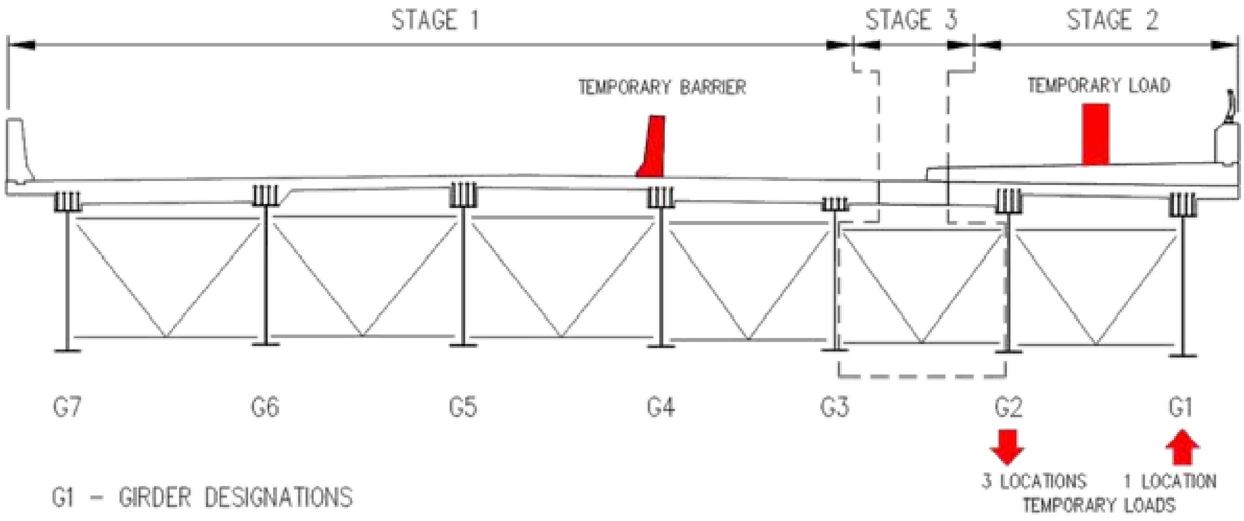

A typical section for the bridge (illustrating sequence of construction).

the out-to-out width varies from approximately 68 ft to 75 ft. The bridge supports four 11-ft lanes of vehicular traffic and a 17-ft-wide, multiuse sidewalk.

Setting the Stage

Staged construction is defined in accordance with AASHTO LRFD as the situation in which the superstructure is built in separate units with a longitudinal joint. This is to be distinguished, and held separate from, the longitudinal deck placement sequence.

The originally proposed sequence of construction for the 11th Street Bridge required all seven girders to be erected and the deck placed using a typical, longitudinal deck placement sequence over the full width of the structure. The bridge sidewalk and barriers were then to be constructed following the placement of the deck. As such, the original design of the bridge did not include considerations for a staged sequence of construction. However, during construction, the contractor decided to re-sequence the maintenance-of-traffic plan for the project, requiring a change in the sequence of construction for the bridge.

But the girders and cross frames were already fabricated and substantially erected based on the original sequence of construction. Therefore, the bridge had to be reanalyzed, not only to check the girders and cross frames for strength, but just as importantly to check the girders, cross frames and deck for camber shape and for relative positioning and fit-up between the stages of construction—all while minimizing the changes to the structural steel.

Another challenge associated with re-sequencing the bridge construction was that the last field sections in Span 1 for girderlines G1 and G2 would not be erected until after the existing 11th Street Bridge was removed; this was due to a spatial conflict between the existing and proposed bridges. As the AASHTO/NSBA Joint Collaboration guideline G13.1-2011 *Guidelines for Steel Girder Bridge Analysis* indicates: “On continuous bridges, girder deflections are influenced by adjacent spans. Just as the presence of girders in one span reduces the deflections in the adjacent spans, when the girders in an adjacent span are not present, deflections are greater.” This phenomenon ultimately led to the implementation of a full-length closure bay to separate the G1 and G2 girder system from the G3 through G7 girder system in the revised sequence of construction.

Rethinking the Plan

Several options were assessed to accommodate the re-sequencing, and the most viable to minimize structural steel changes was to implement a three-stage sequence of construction. Since most of the girders and cross frames were already erected, the decision was made to disconnect the cross frames between G2 and G3 and introduce a closure bay between the two girders, thus creating a five-girder (Stage 1) and two-girder (Stage 2) system, separated by a full-length, longitudinal deck closure pour (Stage 3). This was necessary in addressing the predicted high stresses in the cross frames based on the analysis of the system without the Stage 3 closure pour. The high stresses were the result of the five-girder system deflecting downward under the loads of the deck and traffic, while the two-girder system remained partially erected and for the most part, unloaded.

The revised sequence largely mitigated predicted adverse force effects for the in-place girders and cross frames, but did not fully address the challenges with predicted deflections and relative positioning for fit-up between Stages 2 and 3—a result of the girders and cross frames not being originally detailed for the deflections associated with the revised sequence of construction, as well as the girders in Stage 2 not being fully erected. The design team developed a solution using both temporary and permanent loads strategically placed to allow fit-up of the cross frames and deck in the closure bay once the last field sections for G1 and G2 were erected. The sequence of loading involved the following:

- The traffic barrier, used for the maintenance of traffic in Stage 1, was temporarily relocated in Stage 2 over G4 in Span 5 and over G4 in the remaining spans.
- An opposing temporary force-couple of 30 kips upward force in G1 and 20 kips downward force in G2 was applied in Stage 2 using temporary loads. This was done

to counteract G1 and G2 from twisting away from G3 due to curvature effects and the lack of torsional restraint, since the cross frames were disconnected in the closure bay.

- Temporary downward forces of 20 kips each were applied in Stage 2 on G2 in Spans 2 and 4. These loads were applied to the non-composite girder section to assist in aligning G2 in Stage 2 with G3 in Stage 1. The principle of structural continuity was leveraged by loading one span and obtaining the required deflection in another span.
- A temporary, composite, uniform load was applied on the deck in Stage 2, Span 2 between G1 and G2 using concrete traffic barrier.
- The permanent sidewalk was placed partial-width in Spans 1, 3, 4 and 5 and omitted in its entirety in Span 2 during Stage 2, to further control the relative positioning of G2 with respect to G3.
- The sidewalk barrier was initially constructed only in Spans 4 and 5.

Following the application of the strategic loading, the cross frame connections between G2 and G3 were largely constructable in their relative positions. For the cross frame connections that were out of alignment by more than 3/8 in., details were developed to use air-arc gouging to remove the welds connecting the cross frame members to the original gusset plates, and then replace the existing gusset plates with new pre-drilled gusset plates. The cross frames in the closure bay would first be connected to G2, Stage 2. Subsequently, the new, pre-drilled, gusset plates would be bolted to the connection plates on G3, Stage 1, and then the cross frame members would be field welded to the new gusset plates to achieve the final connection between Stages 1 and 2.

Once all of the cross frames between G2 and G3 were installed, the Stage 3 deck closure pour was placed and the temporary loading in Stage 2 was removed. The remaining portions of the sidewalk and sidewalk barrier were then finished, thus completing the bridge's construction.

Redistributing the Load

During the staged construction operations, the existing cross frame bolted connections were reassembled at all but three cross frame locations within the closure bay. These cross frames were located in Span 2 within the zone where the analysis predicted the largest differential deflections.

As a result of the sequence change, load redistribution occurred within the girder and cross frame system. When compared to the results in the original sequence, some members experienced larger forces, while other members experienced smaller forces. In combination with the countermeasures to achieve fit-up at the connections, 13 out of 276 cross frames within the framing system required retrofit to resist the redistributed larger forces, and limited zones within the bottom compression flanges of G4 and G6 required lean-on bracing to address lateral torsional buckling, since these girders were experiencing higher moments from the redistributed forces.

Modifying the Model

In order to evaluate the effect of the revised construction sequence on the various bridge components, the analysis considered the sequence of loading, the magnitude of loading and the time-dependent stiffness of the girders and deck system, as well as the lateral bracing conditions, during each stage.

The analysis of the staged sequence of construction used the original 2D design model with the necessary adjustments. Due to the complexity of the sequencing of the loads and the ultimate introduction of temporary loadings in Stage 2 construction, multiple design models were required to successfully predict the behavior of the system. Since the behavior of the girders and cross frames remained in the linear elastic range, the individual model results for stresses and deflections were combined using the principle of superposition to predict the behavior during each stage of construction and in the final configuration. Ultimately, nine models were developed, and the results superimposed to achieve the interim and final stresses and deflections.

Successful Re-sequencing

The girder and cross frame fit-up was achieved by strategically using permanent and temporary loads including concrete barriers, concrete sidewalks, concrete block counterweights and a hydraulic jack system to bring the structural steel framing of the two independent stages into relative position for connection. The finished deck slab geometry was achieved by using a full-length closure pour between Stages 1 and 2.

With the rigorous analyses, the revised sequence of construction was successful, achieving girder relative positions and a constructable means for cross frame fit-up. The deck closure pour was placed and the final deck geometry was achieved to obtain both the required structural depth and cross slope geometry of the deck.

Regardless of the complexity of the bridge, consideration of the sequence of construction is critical to reasonably predict the applied loads and the resulting forces and deflections within the system. Whether it is a simple-span tangent bridge built in stages or a multi-span continuous plate-girder bridge, the design must consider the sequence of construction. For bridges that are tangent and mildly skewed, the sequence of construction will dictate the load application on the line girders. For bridges that are curved or highly skewed, the sequence of construction will dictate not only the load application, but also how the dead load and live load forces are distributed through the 2D or 3D girder-and-cross-frame system. As seen with the 11th Street Bridge, re-sequencing the construction caused a redistribution of the loading in the girders and cross frames. Diligently developing the loads for each stage of construction and recognizing the sequential stiffness of the system led to a reasonable prediction of the forces and deflections for girder, cross frame and deck fit-up—illustrating that sequencing indeed matters. ■

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