Solving Skew

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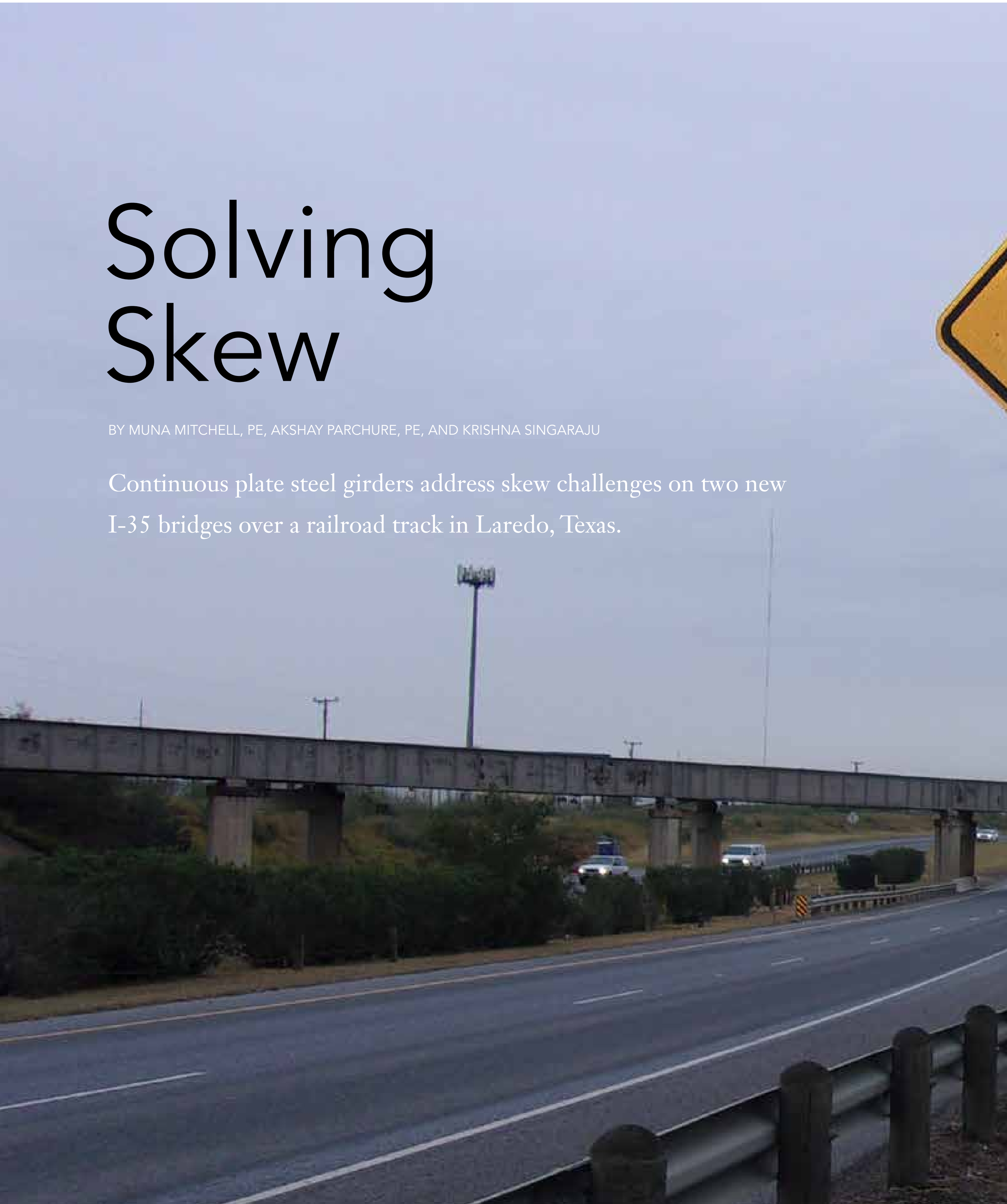
Continuous plate steel girders address skew challenges on two new I-35 bridges over a railroad track in Laredo, Texas.



LAREDO, TEXAS, is the busiest inland port along the U.S.-Mexico border and one of the busiest overall U.S. ports, with large trucks and other vehicular traffic straining the I-35 corridor that runs from the Mexican border north through the city.

At I-35 near Shiloh, the highway crosses underneath a Union Pacific Railroad (UPRR) bridge with substandard vertical and horizontal clearances that pose safety risks and limit expansion of the roadway. To address the situation, UPRR collaborated with the Texas Department of Transportation (TxDOT) to upgrade this section of I-35 by providing additional traffic lanes and decommissioning the existing railroad bridge, which was built in 1960. The solution involved replacing the at-grade traffic lanes with two bridges that clear the railroad right-of-way (ROW) vertically and horizontally while also widening I-35. The grading in the railroad ROW would be altered to result in the tracks being at grade instead of elevated.

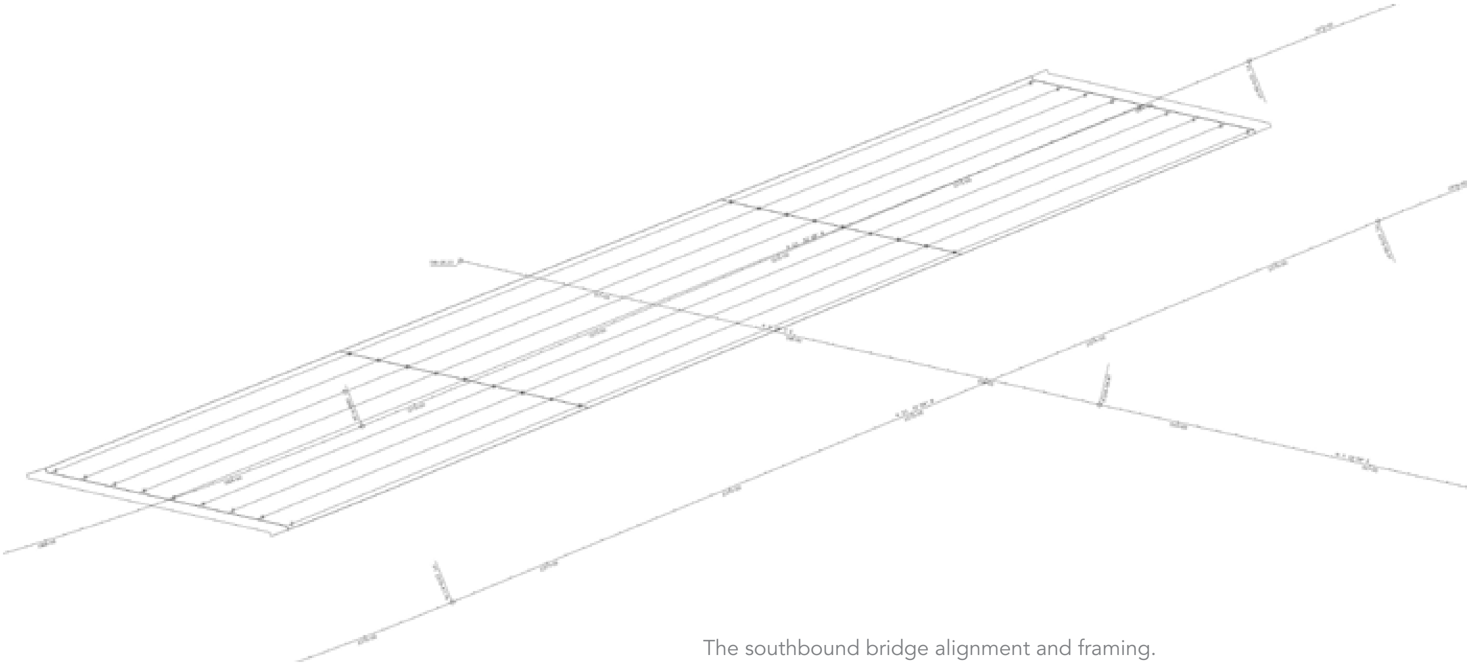
Geometric Constraints

The two new 1,700-ft-long side-by-side bridges carry four lanes of traffic in each direction, with the northbound bridge consisting of 14 spans and the southbound consisting of 15. The approach spans are concrete, and the main spans across the railroad ROW are steel. Each bridge includes a 534-ft-long three-span continuous steel plate unit to address the crossing's significant skew and dimensions, with the span lengths of each unit being 165 ft, 205 ft, and 164 ft. Steel was preferred over concrete for the long spans initially to keep the profile as shallow as possible over the railroad tracks since the vertical roadway curve was constrained by access requirements on either side of the railroad ROW.

The bent lines are oriented parallel to the railroad ROW at a skew of approximately 56° from the roadway alignment. The skews vary gradually along the approach bents by 15° or less to achieve zero skews at the abutments, and the 56° skew is maintained for all four bents in the continuous steel unit on each bridge. The steel units are designed as continuous to optimize the depth of the superstructure at the railroad ROW to meet the vertical clearance requirements while also accommodating the limits of the roadway's vertical curve.

The roadway cross section consists of four 12-ft traffic lanes in a single direction with 10-ft shoulders on both sides. The overall concrete deck is 70-ft-wide in the approach concrete units and varies up to a maximum of 74 ft, 8 in. on the steel unit. This variable width accounts for the roadway curvature while maintaining a straight steel unit to avoid using curved girders. The superstructure consists of nine plate girders with 5-ft, 6-in.-deep webs connected with cross frames at bent lines and intermediate locations along the length of each steel unit. Also, note that since the roadway curve reverses going northbound and southbound, the two parallel bridges are not completely

The existing railroad bridge across I-35 in Laredo, Texas.



The southbound bridge alignment and framing.

identical in terms of girder framing, and all subsequent discussion will focus on the southbound steel section.

Analysis and Design

The girder spacing was analyzed using an initial two-dimensional (2D) grillage analysis with MDX Software with the vertical clearance requirement setting the maximum depth of the structure. Spacing was limited to a maximum of 8 ft to avoid the need for deeper girders, and cross frames were staggered based on AASHTO LRFD and NCHRP guidelines for highly skewed steel bridges. The first and last row of cross frames were kept at a minimum distance of at least 8 ft from the skewed bent line, while the remaining cross frames were equally spaced. Due to the girder geometry, the cross-frame geometry at each location is unique, and cross frames were also provided along all four skewed bents at the bearing lines. To meet the slab overhang limits required by the AASHTO LRFD and TxDOT bridge design manuals, a unique girder spacing was provided in each bay along each bent, making the steel girders not parallel.

The initial 2D model allowed for rapid set up of the girder framing and iterations of plate sizes and girder depth; however, the final design required a more refined model. Based on NCHRP and NSBA guidelines, the cross-frame forces and dead load deflections estimated from a simple 2D grid/2D plate and eccentric beam analysis are not precise enough for a high-skew plate girder bridge. Also, a refined analysis can generate a more accurate output to calculate girder camber values for fabrication. Further, a 2D model is limited in taking the substructure stiffness into account for determining joint movements and thermal forces. As such, the team performed a three-dimensional (3D) finite element analysis (FEA) using Midas Civil software. The bents, columns, and foundations to a structural point of fixity were included in the 3D model, along with the elements of the steel girders and diaphragms to take substructure movements into account when determining the loading on the bearings.

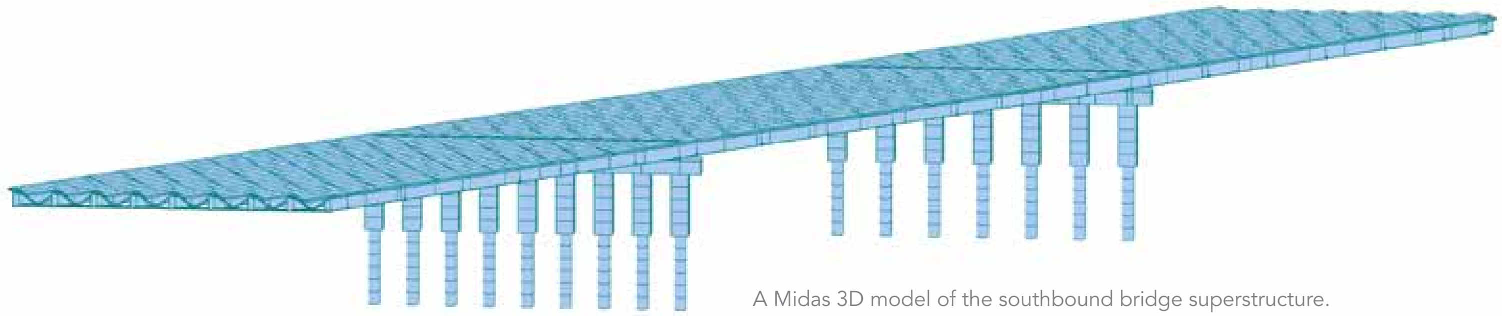
The flange plate changes and bolted splice locations were determined using the analysis results, and the Midas model was used to run multiple iterations and optimize the girder design with design limits for flange and web plates. No longitudinal stiffeners were used, and the only transverse stiffeners needed were to connect the cross-frame members. Since the steel girders were framing at an extreme skew, split pipe connecting plates were used at all bearing locations; these elements also acted as bearing stiffeners.

Initially, three rows of shear studs were proposed to provide composite action between the steel girder and the concrete deck, per the TxDOT standard. However, the number of rows was reduced to two, and shear stud spacing was subsequently adjusted to avoid conflicts around the modular joint and other reinforcing.

Superstructure-Substructure Interaction

The overall width of the bridge is 70 ft. However, due to the variations in skew, the length of the bents varies from 130 ft to 146 ft. In the preliminary design, multi-column rectangular bents were considered at all bents. Inverted T bent caps with joints on either side of the stem were later implemented at transition bents, and rectangular bent caps were used at the concrete units and for interior bents on steel units. With an inverted T bent, a joint could be used on either side of the stem, reducing the total movement in a single joint. The inverted T bent also allowed the use of a modular bridge expansion joint (MBJS) that requires the support of the stem for the joint system.

The decision to use inverted T bents evolved during the design process as the full impact of the geometry and movements were realized. The change from rectangular to inverted T bents was made late and required changes to preliminary bent designs. To avoid redesigning the steel girders, the locations of the end bents were shifted to maintain the bearing lines at the ends of the steel units. This decision prevented changes to the girder designs but caused changes to the bridge layouts because the centerlines of bents, columns, and foundations were shifted outward from the right-of-way lines, requiring coordination with other disciplines and verification of horizontal clearances from U-turn lanes on either side of the railroad ROW.



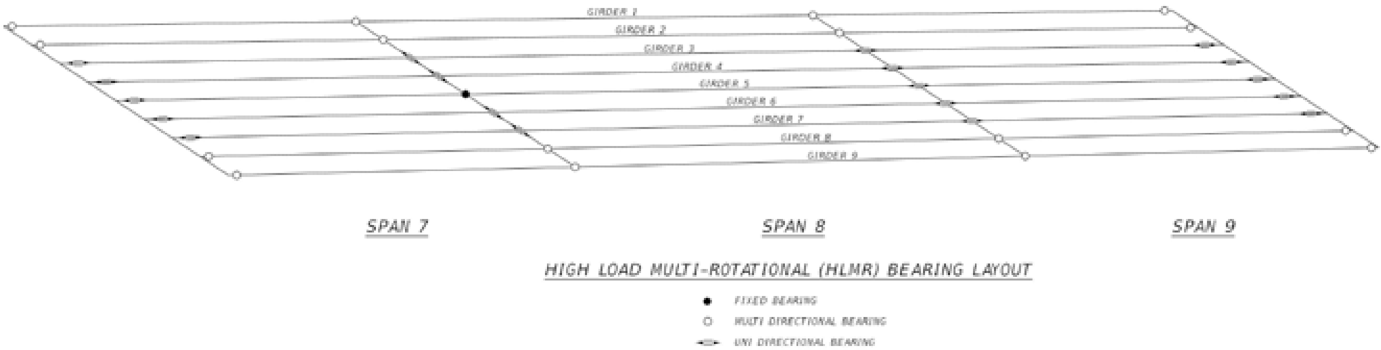
A Midas 3D model of the southbound bridge superstructure.

The designs for the substructure and bearing configuration were driven by the effect of transverse forces due to thermal loads and live loads. The preliminary FEA models did not have the substructure modeled, which resulted in improper boundary conditions and inaccurate thermal forces. To accurately capture the effect of transverse forces, it was necessary to model the substructure and assign appropriate translational and rotational properties to the bearings.

Several FEA models were developed to study the various bearing and bent configurations before determining the final configuration. In the initial study, bearings at both the interior bents were fixed against translation in all directions to limit the demand on the expansion joints. However, this approach resulted in significant forces on the bearings, so it was decided to use fixed bearings at only one interior bent. Bearings at the other interior bent are fixed in the direction transverse to the girders.

Skewed steel bridges expand and contract along the diagonal connecting the acute corners of the slab under thermal loads and not along the alignment parallel to the girders. This behavior results in twisting in the deck, so the thermal forces are not distributed equally to all the bearings. The thermal forces in the bearings increase from the center outwards, resulting in significantly high forces in the outside bearings. Instead of designing for these high forces, the team decided to use free bearings at the outside two girders on both sides of the bridge centerline, resulting in five fixed interior bearings.

The team decided on a single bent cap approach instead of separating each bent into multiple frames as the single frame would help balance the out-of-plane forces in the cap without transferring them to the substructure. Even with five fixed bearings, the transverse forces were significant on the bearings, which complicated the design



A bearing layout diagram for the three steel spans.

of the bent cap as these elements need to be designed for out-of-plane forces and torsion in addition to in-plane forces. To reduce the in-plane bending, columns were provided at each girder.

Bearing Fixity

During the letting stage, the bearing manufacturer determined that the transverse forces in the bearings were still significantly high and, as such, it would be difficult to manufacture the bearings. It was determined that instead of using bearings that resist translation in all directions, they could be fixed in only the longitudinal direction, thereby reducing the transverse forces. The orientation of the bearings also influenced the transverse forces developed in the bearings. In addition, fixing the bearings along the skew and normal to the bent instead of fixing them normal to the girders would further reduce the forces in the bearings.

To achieve constructable bearing loading, the team decided to further reduce the fully fixed bearings. Since the center bearing does not see high transverse forces, it was fully fixed in all directions, and the two bearings on either side of the center were fixed in the direction normal to the bent but free to move in the direction along the bent, with the outer two bearings on both sides free to move. This option reduced forces on the bearings significantly and was within the force range determined by the bearing manufacturer. The girders were evaluated for any changes based on the bearing design, and no changes in the girders were discovered.

There is an increasing need for medium- to long-span steel bridges with complex geometry due to site restrictions in developed areas. One solution to addressing grade separations in congested areas is to use continuous steel girders on skewed supports. This method can allow the bridge superstructure to avoid at-grade obstructions, limits impacts to the foundation, and addresses vertical clearance constraints, as demonstrated by this project. ■

*This article was excerpted from the 2022 NASCC: The Steel Conference session "Curves Ahead: Case Studies on Skewed and Curved Girder Bridge Design," which highlighted two plate girder bridge designs and was presented by Muna Mitchell of Walter P Moore and Meng Sun, SE, PE, PEng, of Parsons Corporation. A recording of the presentation will be posted at **aisc.org/educationarchives** in early May.*

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Webber

Structural Engineer
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Steel Team

Fabricator
W&W|AFCO Steel, San Angelo, Texas

Detailer
Precision Drafting, LLC, Bergenfield, N.J.

Muna Mitchell is the managing director for transportation bridges, **Akshay Parchure** is a senior engineer, and **Krishna Singaraju** was an associate bridge engineer, all with Walter P Moore.