CURVED, VARIABLE DEPTH, SINGLE STEEL TRAPEZOIDAL BOX GIRDER PEDESTRIAN BRIDGES

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BIOGRAPHY

Karthik Ramanathan has 20 years of experience in designing steel and concrete bridges for highways, airports and rail projects. He is a Senior Bridge Project Manager at Stantec. He was the bridge team lead on the SH 288 project, for a 1.33-mile-long direct connector and the Southmore Steel Pedestrian Bridges. He has an undergraduate degree from the Indian Institute of Technology, Madras and a Masters from Arizona State University.

Annus Ahmed is a Structural Engineer at Stantec. He has experience in design-bid build projects and design-build projects. He has designed steel and post tension straddle bents in Texas and designed several curved steel bridges with complex geometry. He is currently working on a steel railroad via-duct for a fast-paced design build project in Chicago. He did his undergraduate work from National Institute of Technology, Trichy and masters at University of Texas at Arlington.

Seng Sok is a structural engineer at Stantec with over 6 years of experience in designing highway bridges in Texas, Alabama and North Carolina. He has worked on three design-build projects with experience in the proposal, design, and construction phases. He graduated Summa Cum Laude with a Bachelor’s in Civil Engineering and a Master of Science degree from University of Houston.

SUMMARY

Stantec designed two horizontally curved, variable depth trapezoidal steel box girder bridges as part of a design build/P3 project. The aesthetic concept was chosen by TXDOT as a unique “signature” bridge that serves as a gateway to the northern limit of the SH 288 toll lane project in Houston which is a heavily travelled corridor in Houston with a confluence of three freeways.

A steel box girder was chosen over concrete to meet the requirement of variable depth superstructure, provide a pre-fabricated option to erect and minimize impact to traffic under the bridge and be the most cost-effective option for these bridges. Various design and detailing requirements for horizontal curvature, fracture critical, variable depth steel superstructure will be discussed in this paper. In addition to strength, frequency, fatigue, fracture, deflection and vertical clearance are considered in this design. These bridges had the confluence of aesthetic form, design and functionality blended into one.

INTRODUCTION

The State Highway 288 (SH 288) Project is a public-private-partnership (P3) project located in Houston, TX. The project when completed, will construct toll lanes from US59 to the Clear Creek Harris County Line. There are 42 bridges on the project, with concrete and structural steel superstructures and concrete substructures extensively used throughout the project. Stantec is the lead design firm on the project, that is being constructed by a consortium of contractors “Almeda-Genoa Contractors” (AGC).

At Southmore Blvd, there is an existing bridge that connects the east and west side of the 288 freeway. This cross-street is an important connection between Texas Southern University on the east and the Houston Museum District on the west side, which includes the Childrens’ Museum of Houston, Holocaust Museum, Museums of African American Culture, Fine Arts and Natural Science. Therefore, providing a pedestrian access between the two sides of the freeway is a desirable outcome for the community in this area.

The picture below, shows the area of the project and the specific location of the bridge.

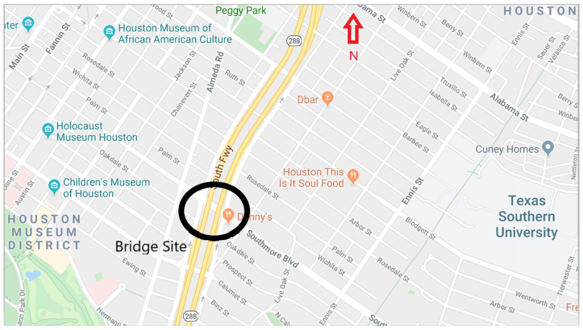


Figure 1: Project location

As construction was progressing on the project in the years of 2017-2018, there was discussion at TXDOT on providing a separate pedestrian access on the north and south side of the new skewed roadway bridge at Southmore Blvd. This would also form a “signature entrance/exit” to the project at the north end. Originally, the Southmore Blvd bridge was designed with a raised sidewalk to convey the pedestrian and bike lane traffic. However, due to ongoing discussions and desire of constructing two separate pedestrian bridges on each side, the skewed abutments of the new roadway bridge at Southmore Blvd were designed to accommodate this possibility. In July of 2018, Stantec was tasked with providing a preliminary design and fee estimate for two pedestrian bridges on each side of the Southmore Blvd Roadway Bridge, which had been partially constructed, to convey the Eastbound (EB) and Westbound (WB) pedestrian traffic. The estimate was based on an aesthetic concept chosen by TXDOT and provided to Stantec.

The aesthetic concept showed two horizontally curved bridges that had a variable depth mimicking an arch. The bent locations were adjacent and nearly parallel to the bents of the roadway bridge, while the already over-built abutment would be used for the pedestrian bridges. The bents also required a flared column that would blend the curvature of the column and the parabolic shape of the bridge soffit. The preliminary model created to enumerate the aesthetic drawing provided to us by TXDOT is shown below.

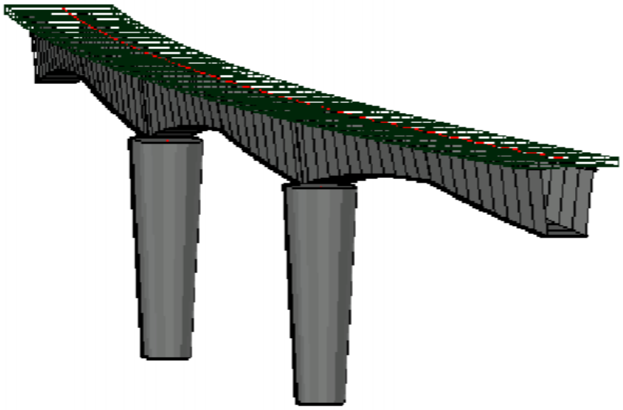


Figure 2: Perspective 3-D view of the bridge

STRUCTURE TYPE SELECTION

From the aesthetics and the partially constructed information on the roadway bridges, Stantec developed conceptual level plans for the contractor. The approximate span configuration for the EB Bridge is 108’-88’-105’. To keep the two bridge designs the same with respect to the curvature, the span layout of the bridge on the WB side was inversely set as 105’-88’-108'. During preliminary discussions, potential span to depth ratios for this bridge, given that the soffit had to vary parabolically, were determined. From this analysis, and the vertical clearance requirements for pedestrian bridges of 17’-6” minimum required, the web depth at the supports was set as 72” while at midspan it was set as 36”. In general, the span to depth ratios for steel bridges from the AASHTO LRFD code is approximately 1/32 of span. During this preliminary design phase, the type of superstructure that would be feasible for these bridges was also determined, to provide TXDOT an accurate estimate of cost and to get their approval prior to commencing final design. Due to the variable soffit, a steel trapezoidal tub girder structure and a cast in place post-tensioned or reinforced concrete box girder bridge were considered as feasible structure type options. Typical Precast Concrete I-Girders or Tub Girders were not considered feasible, as they would have required extensive modifications to their preset forms, strand beds or would require post-tensioning to accommodate the variable depth, just to fabricate six beams. Given that the project did not have any other segmental bridges and the narrow width of a pedestrian bridge, it was not considered economical for these structures to use segmental construction, especially to meet the cost estimate that TXDOT had in mind for this work. For the cast in place concrete option, falsework would be required over a heavily traveled freeway and newly operational toll lanes, which the concessionaire wanted to avoid. Therefore, the use of a structural steel trapezoidal box girder was considered most economically and structurally feasible for these bridges. Structural Steel also lent itself to be painted or to use weathering steel and provide the client an aesthetic finish choice. Painted steel was chosen as the preferred option to be consistent with the other bridges on the project and to provide flexibility with the color to be used on the bridge superstructure. Grade 50 ASTM A 709 Steel was specified as it is suitable for painting. The bridges would also have two special pedestrian fences that were to be lit. The typical section submitted with the preliminary design is as shown below.

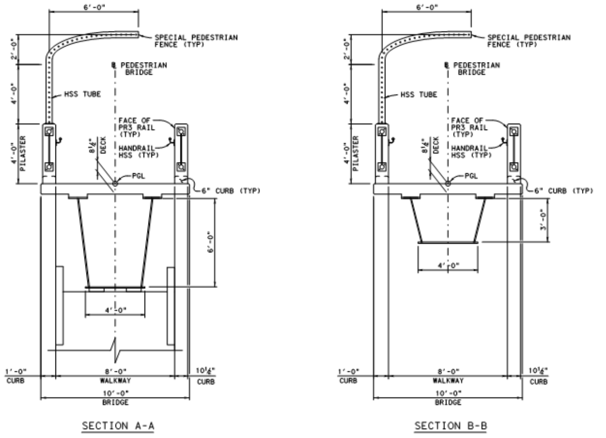


Figure 3: Preliminary Cross Section

DESIGN REQUIREMENTS

After submitting the preliminary design and based on the acceptance of the concept, notice to proceed was provided to design the twin steel pedestrian bridges. The design was in accordance with the AASHTO Guide Specifications for Pedestrian Bridges. In addition to this code, the design needed to satisfy the requirements of the AASHTO LRFD Design Code, for design, detailing and code checks.

Since these pedestrian bridges were 10 ft wide, only a single trapezoidal box would be feasible. This resulted in these structures being fracture critical. According to the project technical provisions, special written permission was required for any structure deemed fracture critical. Fracture critical bridges require special design and fabrication considerations, such as calling out fracture critical members on the plans, adhering to Fracture Control Plan, fabricator qualification, and construction inspection requirements. In addition, to meet the in-service inspection requirements for fracture critical structures, TXDOT required that the inside of the bridge be painted white, fully lit and access holes be provided at regular intervals. Also, TXDOT preferred practices outline avoiding fatigue details more critical than Category C for fracture critical members. Typical trapezoidal box girders of constant depth only require one or two access holes, since it is feasible to walk from one end to the other, especially if it is deeper than 6ft. However, due to the variable depth and narrowness of the structure, it was deemed that this structure would receive a total of six access openings, one each at the end of the three spans, at the deeper sections, close to the substructure.

The design considerations of these pedestrian bridges were primarily divided into the following categories.

GEOMETRIC CRITERIA-

Geometry is the primary consideration when designing and detailing any bridge. It determines the boundary conditions for the design and informs many of the decisions. This was especially true for these pedestrian bridges, given the variable depth, skewed ends, narrow width and curvature. **The primary challenge was to fit all required details such as cross-frames, lateral bracing, splices, access holes, jacking stiffeners, bearings, end diaphragms and bearing stiffeners within the room available, while satisfying all the design requirements**.

1. Influence of Plan Geometry-

   a. Horizontal geometry (curved girder)- The AASHTO LRFD specifications state that a single-girder torsionally stiff superstructure, except for concrete box girder bridges, maybe analyzed as a curved spine beam. With regard to analysis, the LRFD specifications state that box girder beam superstructures have not been as closely examined with respect to approximate methods. Therefore, a 3-dimensional model was deemed to be required.

   b. For Closed Box and Tub Girder Steel bridges, with the radius of 1509’ and a maximum span of 108’, the arc span of 0.07 rad was less than 0.3 rad. The girder depth at midspan is less than the narrowest width at the mid-depth but the maximum depth of the girder was not less than the narrowest width of the beam. Therefore, the effect of curvature could be ignored only if the bearings are not skewed. **Since the bearings were skewed and the section depth varied, it was required to analyze the structure as a curved spine beam in three dimensions.** In addition, to accurately model the frequency, the bridge was modeled in MIDAS as a 3-dimensional beam. Separate models were set up in STAAD and CSI Bridge to calibrate the results achieved in MIDAS.

   It is vital to note that no commercially available program completely covered the interim loading/deck pour considerations that come into play for single steel trapezoidal boxes. Additional checks like the 1/3rd rule for curved bridges, splice design, camber were added with supplemental calculations. Similar discussions presented in the 2012 AISC paper titled “Current design practices for curved trapezoidal steel box girders –a case study”, by Kochersperger and Crozier. (Reference 9), were reviewed for design.

2. Vertical Clearance- The existing features controlled the vertical clearance to the pedestrian bridge. Per the AASHTO Guide Specifications, 17’-6” vertical clearance is required for pedestrian bridges. For aesthetics and because the abutment was already constructed, it was preferred to keep the pedestrian bridge profile close to the roadway bridge. **The vertical clearance for this bridge determined the maximum depth of the superstructure, especially given the need to have flared columns at the bents.**

3. Existing abutment skew- Due to the new Southmore Roadway Bridge Abutment

already being built, the skews at the ends could not be avoided. The abutment skew restricted the possibilities on connection of the last bays of the X-Frames and the top flange lateral bracing. Potential remedies for this were using gusset plates or using a welded connection. During the fabrication process, we decided to use gusset plates, to keep consistent with the typical connection of lateral bracing to top flanges. However, welding could have been used for pedestrian bridges, given that fatigue load is not a major consideration.

LOAD CRITERIA-

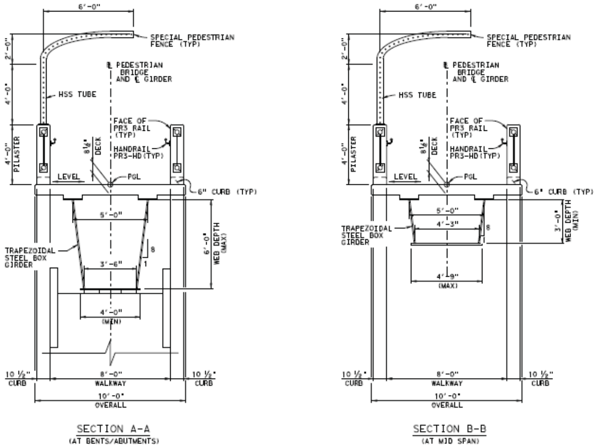
1. Dead load, barrier and fence loads- dead load includes a permanent metal deck form, haunch and slab, weight of lighting inside, curb and fence. No wearing surface is required per TXDOT policy.
2. Pedestrian Live Load- Pedestrian live load of 90 psf is applied to the deck width.
3. H-10 Maintenance Truck- Per TXDOT requirement, needed to design for maintenance vehicle, which was deemed as equivalent to H-10 load
4. Wind Load- per the AASHTO Guide Specifications, the superstructure of the bridge must be designed for the wind load from the AASHTO Standard Specifications for Highway Signs. This resulted in a wind pressure of approximately 75 psf applied to the superstructure.
5. Deflection – Per AASHTO Guide specifications, the deflections for service limit state shall not exceed Span/360.
6. Fracture - Since bridges are classified as fracture critical the Charpy V-Notch fracture toughness requirements apply.
7. Vibration/Frequency considerations- per the AASHTO Guide Specifications for Pedestrian bridges, the fundamental frequency of the bridge in the vertical direction shall be greater than 3.0 Hz, and in the horizontal direction shall be greater than 1.3 Hz.
8. Fatigue- No vehicular volume. Per AASHTO Guide Specifications- design for truck induced wind gust case and natural wind gust cases need to be considered from the AASHTO Standard Specifications for Highway Signs. No details more critical than Category C allowed for Fracture Critical Members.
9. Bearing Design- Research and case studies have been done as part of TXDOT projects outlined in “Elastomeric Bearings for Steel Trapezoidal Box Girder Bridges”, Timothy E. Bradberry, P.E., Jeffery C. Cotham, P.E., and Ronald D. Medlock, P.E. (Reference 8). Based on these case studies, other project examples and the design calculations, the use of single elastomeric bearings was deemed appropriate at all the abutments and interior bents.

In summary, for pedestrian bridges, the design requires using three different AASHTO specifications, in order to completely meet the design criteria.

BOUNDARY CONDITIONS-

Once the final design commenced, the final bridge cross section was required to be established. Due to the variable depth, one of the primary choices for the section was to decide whether the bottom flange would be constant width or variable. If the bottom flange was constant width the web slope would have to vary resulting in warping in variably cut web plates. With a variable width bottom flange, it would allow the web slope to be constant throughout the bridge and would keep the developed elevation of web to remain planar. This would eliminate warping otherwise developed due to variable web slope. To prevent web warping and to have a uniform visual appearance in elevation for the webs, it was determined that the web slope would be constant while the width of the bottom flange would vary. A certain minimum width at the bottom flange needed to be provided to facilitate inspection at the narrowest sections.

Based on this the final typical section of the bridge was set, which was a refinement of the initial typical section by varying the bottom flange and keeping the web slope constant. This section is shown below:



SECTION A-A (AT BENTS/ABUTMENTS)

SECTION B-B (AT MID SPAN)

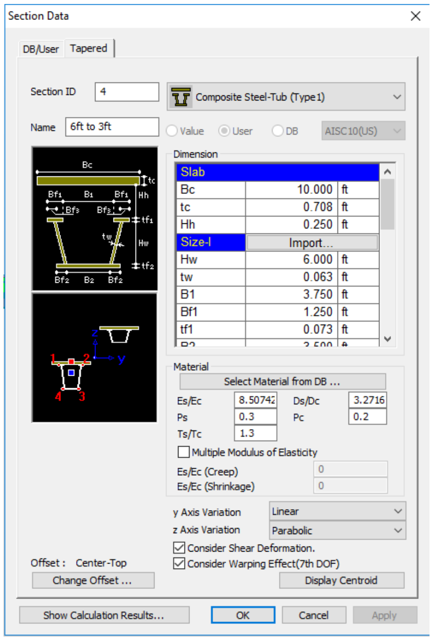
Figure 4: Final Design Cross Section.

Since the bridge was curved and there were two bridges to be designed/detailed in a short time, the same span configuration with reference to the curvature was used to have a single analysis model. The boundary conditions/fixities were also chosen accordingly as Expansion (E)-E-Fixed(F)-E for EB Bridge and E-F-E-E for WB Bridge. In addition, the skews at the abutments also resulted in a situation where the same framing plan could be utilized for both bridges. This would allow the use of the same details for both bridges, for most part. The only difference between the EB and WB bridges was the location of the splice, because they did not occur at the same location with respect to the individual bridge span but were at the same location on the roadway underneath.

The design modeling of the pedestrian bridge was done in the MIDAS program.

ANALYTICAL MODELING

Given the challenging geometry of the Steel tub as described, it was difficult to capture all the aspects of the tub girder typically used industry standard software such as MDX. MDX has the capability to model single tub girder with variable depth but it can be modelled only as a line model and doesn't account for the curved geometry, as required for this bridge. Therefore, tapered section features in MIDAS which allows to vary the depth of tub parabolically in longitudinal direction was used to model the exact geometry as shown in the figure below.



Section ID: 4
Composite Steel-Tub (Type1)
Name: 6ft to 3ft
○ Value ● User ○ DB AISC10(US)

Dimension

Slab		
Bc	10.000	ft
tc	0.708	ft
Hh	0.250	ft
Size-I	Import...	
Hw	6.000	ft
tw	0.063	ft
B1	3.750	ft
Bf1	1.250	ft
tf1	0.073	ft
B2	2.500	ft

Material
Es/Ec: 8.50742
Ds/Dc: 3.2716
Ps: 0.3
Pc: 0.2
Ts/Tc: 1.3
☐ Multiple Modulus of Elasticity
Es/Ec (Creep): 0
Es/Ec (Shrinkage): 0
y Axis Variation: Linear
z Axis Variation: Parabolic
☑ Consider Shear Deformation.
☑ Consider Warping Effect(7th DOF)
Offset : Center-Top

Figure 5: Tapered section feature in Midas.

Line model was created for longitudinal analysis and design. Figure 6 shows an isometric view of the model in MIDAS.

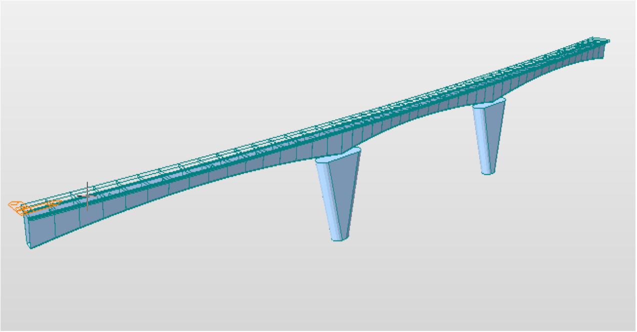


Figure 6: Isometric view in Midas.

Cross frames were also modeled as beam elements to capture the bracing along the bridge as shown in Figure 7, these were connected by rigid links to the tub girder. Rigid links with appropriate stiffness were used to assign end fixities at supports. As the geometry was exactly modeled, MIDAS calculated the self-weight of the steel tub structure including the weight of the concrete slab. Dead load contribution of barriers, haunches and other miscellaneous loads were hand calculated and entered as line loads. Live load which includes 90psf pedestrian load and H10 truck were applied as a lane load. Wind load per design specifications was applied as a line load.

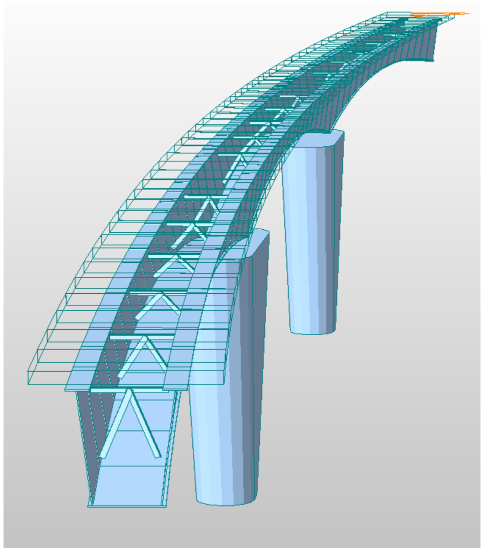


Figure: 7 Cross section in Midas

MIDAS can capture the composite and non-composite behavior which was convenient to check stresses under construction stages as well as final strength cases as shown in Figure 8.

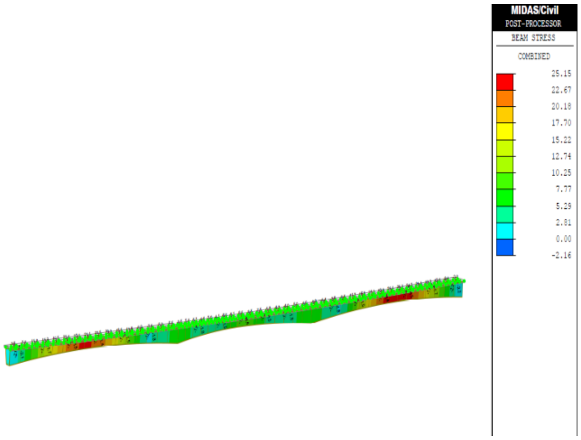


Figure 8: Stress under strength cases

As a project technical requirement for pedestrian bridge an eigen value analysis was also conducted and the natural frequency of the bridge was computed using MIDAS. As the natural frequency was higher the minimum required frequency no further dynamic analysis was required. Fatigue stress checked for natural wind gust and truck induced wind gust were very low and there were no critical fatigue details that controlled the design. Transverse analysis and design of cross frames, end diaphragms bearing and jacking stiffeners were performed using spreadsheets by extracting the loads from MIDAS.

INDEPENDENT DESIGN

Due to the unique nature of the bridges and as part of the project QC/QA process, an independent design review was performed by an engineer who was not involved in this project. Combination of MDX and CSI bridge were utilized to perform independent checks which were consistent with Design results from MIDAS . For this exercise in MDX, line girder model with straight geometry was used while line girder with curved geometry was incorporated in CSI Bridge. The girder was constructed by frame elements and deck was modeled as plate elements. Figure 9 shows an isometric view of CSI bridge model.

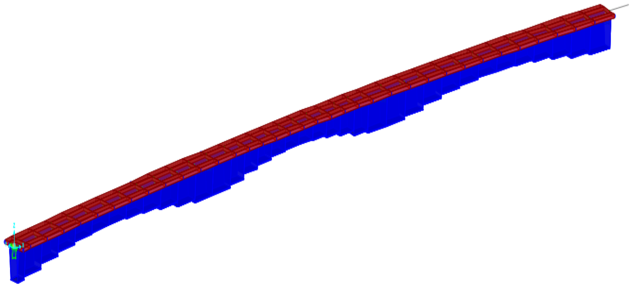


Figure 9: Isometric view in CSI

DETAILING REQUIREMENTS

The detailing of these two pedestrian bridges needed to satisfy the structural strength as well as functional and inspection requirements. The unique feature of pedestrian bridges is the narrow width that is available to fit all the elements required, as opposed to a vehicular bridge, where more room is available.

For this, the following had to be carefully detailed-

1. Plate sizes determined based on strength, frequency, deflection requirements. The bottom flange width was governed by consideration for plate distortion during fabrication and erection. TXDOT practice preference is to use 1” minimum bottom flange tension plates for box girders (Reference 5). Webs were constant slope 8:1 and same thickness, but varying depth. Top Flange thickness was maintained the same in order to avoid variable and eccentric details for lateral bracing attachments by adding shims or fill plates.
2. X-frame spacing determined based on strength requirements. The spacing also had to accommodate the lateral bracing design, end skews, access opening and field splice requirements.
3. Top Flange Lateral Bracing design based on deck pour, horizontal curvature requirements. Based on past project experience and commentary from FDOT, a Warren truss configuration for lateral bracing was considered the most optimal.
4. Splice locations to be determined based on maximum lifting restrictions for tub girders of 140 ft or maximum width including sweep to be below 14 ft (Reference 5), and traffic below the bridge due to heavy volume and avoiding splice towers in toll lanes.
5. Access hole locations to be determined based on availability/ease of access for inspections and to be far enough away from the substructure outlay.
6. Access holes and splice locations by nature, end up being located close to each other, as they are near the supports and therefore could be adjacent to each other. However, some clear distance is required from the access holes to the splice.
7. Lighting details required for inspection- Coordination was required with the Illumination Engineer to deal with the permanent lighting required inside the bridge and to provide the required conduit, luminaire and power source.
8. End Diaphragms along the abutment skew – Special End Diaphragms were detailed at each end to accommodate the different skews.
9. Bearings at skew- Typical bearing details would have been outside the bottom flange. However due to the skew of the built abutment, this option was not feasible. Therefore, the bearing details were under the bottom flange, within the webs. These two details (End Diaphragm and Bearing) are shown in the Figure 10.

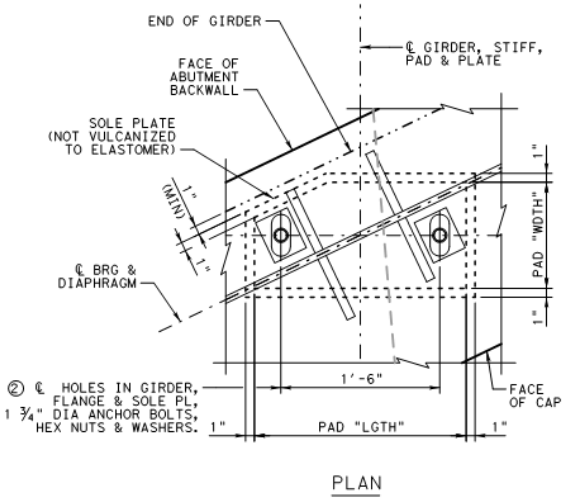


Figure 10: Skewed End Bearing

FABRICATOR COORDINATION

Since this project is a design-build/P3, it was decided to use the process to our advantage by submitting our advanced design plans to a fabricator of the contractor’s choice (Hirschfeld). The purpose of this review was to ascertain if the design plans were providing adequate information to the fabricators to be able to build the steel girders. In addition, it would also provide us feedback on some of the more non-typical details such as the access opening and variable bottom flange. However, since this fabricator was not contractually required or formally chosen to set up the bridge into their system and draw it out, this process was only used as a cursory review, which needs to be considered in the detailing process. For example, a fully 3-D model could be created during design, if this is deemed feasible and there are tools available to do so. Generally, the scope of the design is not to generate shop drawing level plans, therefore, this process needs to be discussed with clients on a case-by-case basis.

After the bridge design plans were issued for construction, the contractor negotiated with a fabricator to bid on the pedestrian bridge fabrication. King Fabrication, located in Houston, was chosen through this process. King Fabrication has major steel bridge, fracture critical endorsement and the sophisticated paint endorsements, which were required for this bridge. During the shop drawing development process, the fabricator had a few questions/comments as they progressed with putting together their shop drawing package. The primary area of questions were the skewed ends and splice detailing with reference to top flange lateral bracing. For the skewed ends, providing gusset plates to accommodate the skewed end connections were considered as shown in Figures below:

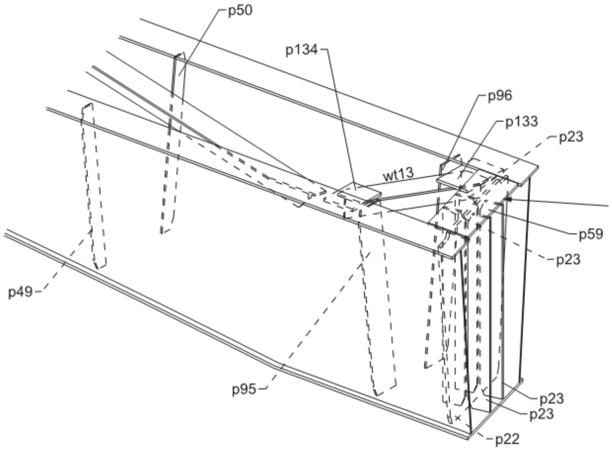


Figure 11: End Skewed Gussets (1)

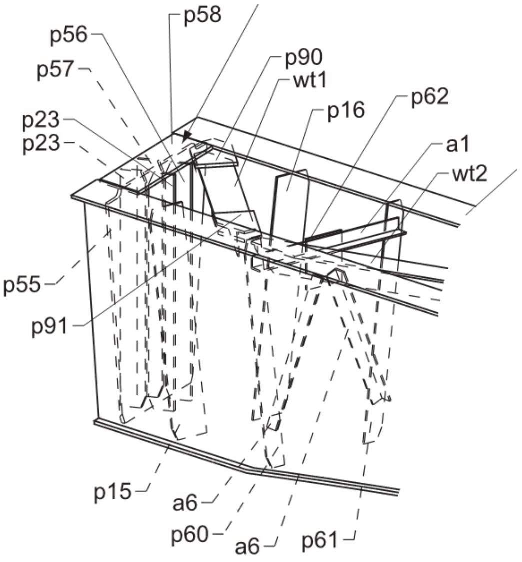


Figure 12. End Skewed Gussets (2)

For the bracing at the splice, one bay was substituted with an angle instead of the typical WT section. The slenderness of the angle had to be checked for the bracing forces, as the capacity of the slender angle is less than the symmetrical WT section. Also, the availability of angle sections in Grade 50 has become almost as common as Grade A36 and hence the substitution was possible to avoid a coped WT section. This is shown in Figure below:

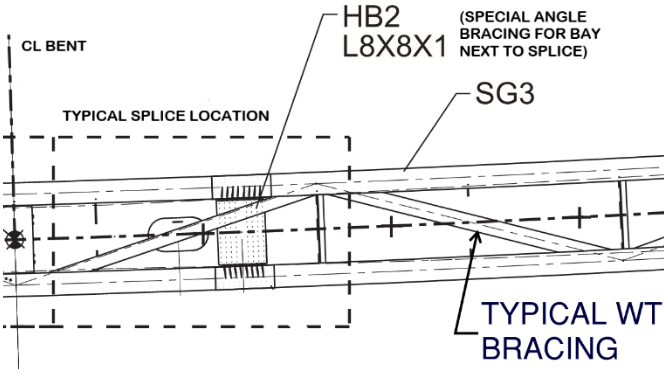


Figure 13: Angle Lateral Bracing at Splice

The 3-dimensional representation of the bridge from the shop drawings, as “assembled” is shown below to provide an idea of the various elements that go in the detailing of a steel trapezoidal girder bridge.

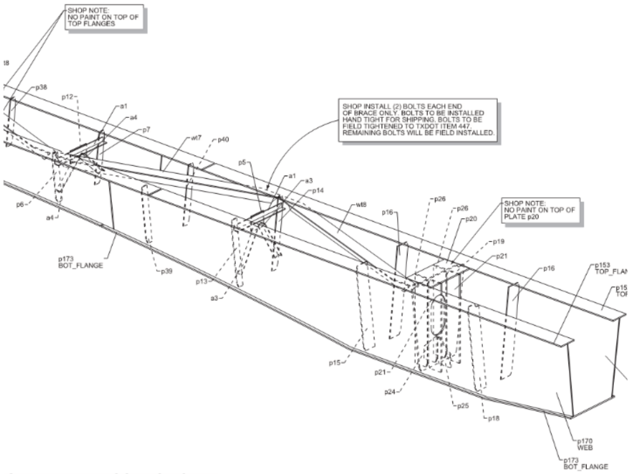


Figure 14: 3 Dimensional View of Shop Drawing

CONCLUSIONS

This paper illustrated the process of designing and detailing of two curved, variable depth trapezoidal box girder steel pedestrian bridges with single girders. During the preliminary design, a structure type selection was performed. Reinforced or post-tensioned concrete box girder or segmental construction were considered. However, given the variable depth required by aesthetics, heavy volume of traffic under the bridge and the ease of pre-fabrication using tapered steel sections, structural steel was the most economically and structurally feasible alternative. The versatility of structural steel to be able to provide a constantly tapering section, which provides a more uniform aesthetic appearance, as well as the cost-effectiveness of construction and erection over traffic ultimately won out. Steel also lent itself to not having joints between segments or form liners and to be painted to a color of the client's choice, given that the bridge was required to be aesthetically pleasing. This option was not without its own challenges as the bridges are deemed fracture critical, as they only have one girder each. The fracture critical nature of the bridges imposed additional requirements on the design, fabrication and future inspection teams that were overcome by some unique design and detailing. Pedestrian bridges in general require special design considerations in addition to service and strength, such as frequency, deflection, wind load, fatigue considerations. Additional detailing and fabrication requirements are imposed when these bridges comprise of Fracture Critical Members. Per TXDOT requirements for in-service inspection, access holes are provided at each side of each bent and abutment, so that there are a total of six access holes on each bridge. Each bridge will have the inside painted white and will be permanently lit inside to facilitate inspection. This specific design required to accommodate curvature, skewed ends at the abutments and variable depth section in profile. This complex geometry led to some unique details such as gusset plates at the end bay for the lateral bracing attachment, skewed bearings at the abutments within the bottom flange width, variable width bottom flange with constant slope webs to accommodate the variable depth of the girders. These details are outlined and presented in this paper.

ACKNOWLEDGEMENTS:

1. TXDOT Houston District.
2. Almeda Genoa Contractors (AGC), Houston TX.
3. King Fabrication, Houston, TX
4. Elizabeth Gilbert, Oscar Gutierrez, Joe Guerrero, Ali Mirnami (Stantec)

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