A CASE STUDY: Hiawatha LRT, Lake Street Bridge, Minneapolis, MN

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ABSTRACT

This is a case study of the first use of post-tensioned concrete box girder structure for Light Rail Transit in Minnesota. Parsons was the Engineer of Record for this fast-track design-build project. Structure type was selected after an exhaustive cost evaluation with input by the design-build partnership and the owner. This case study addresses why a post-tensioned concrete box girder bridge is the best structure type for economic, maintenance cost, initial construction cost, and aesthetic reasons. It also addresses unique design challenges for the structure, which include a non-linear analysis of the rail-structure interaction due to direct fixation track. Finally, a discussion will be given on contractor-requested design changes consistent with the economies specific to this contractor.

Keywords: Design-Build; Fast-Track; Light Rail Transit; Post-Tensioned; Concrete Box Girder.

INTRODUCTION

The Hiawatha Light Rail Transit (LRT) is an 11.6-mile design-build project that will connect downtown Minneapolis to major outlying locations. The Hiawatha Project Office, the system's owner, broke ground on January 2001, and construction was started on the largest publicly funded project ever undertaken in Minnesota. Partial service is scheduled to begin in late 2003 with full service slated to begin in December 2004.

When complete, this system will link some of Minnesota's highest traffic generators including downtown Minneapolis, Nicollet Mall, the University of Minnesota, the Minneapolis / St. Paul International Airport, and the Mall of America. Ridership is projected to be over 19,000 per day in the year 2004 and climb to over 24,000 riders per day by the year 2020. This $675 million project includes 17 transit stations, 14,800-ft of tunnel, two major flyover bridges and the modification of numerous existing railroad bridges for light rail use. This paper concentrates on one of the more challenging aspects of the project — the Lake Street Bridge and Station Structure.[1]

LRT Map[2]

The Lake Street structure comprises the Lake Street Bridge and Station and is a vital part of the system. This important link carries the LRT over TH-55 (Hiawatha Avenue), a six-lane thoroughfare with center median, Lake Street and 28th Street. It consists of 15 spans divided into four units for an overall bridge length of 2,072-ft. and a maximum span length of 185-ft. The superstructure is made up of both single and double cell post-tensioned concrete box girders 8.5-ft deep. It carries two LRT tracks on a ballasted deck, in addition to a 335-ft. long by 26-ft. wide elevated transit station supported by the bridge and located directly over the Lake Street intersection. The station framing consists of precast prestressed "I" beams supported by cross struts framed directly into the single cell box girders.

DESIGN-BUILD

The Granite/McCrossan Joint Venture teamed national and local firms to tackle this first-of its-kind project in the State of Minnesota, combining light rail and design-build. Each joint venture team member complemented the capabilities of the other. Granite Construction of Watsonville, California brought extensive resources and wide breadth of construction experience to the project. C.S. McCrossan, of Golden Valley, Minnesota, contributed local experience, regional understanding and manpower. While post-tensioned concrete box girders are not prevalent in Minnesota, both Granite and McCrossan have experience with construction of post-tensioned concrete box girders, with Granite having completed many such bridges along the West Coast and across the nation and McCrossan having recently completed similar bridges in Minnesota. Parsons headquartered in Pasadena, California, was chosen as the designer for the Lake Street Bridge based on past successes on similar design-build projects. Parsons brought the ability to draw on a large resource of technical staff to complete this design task within the contractor's aggressive time frame.

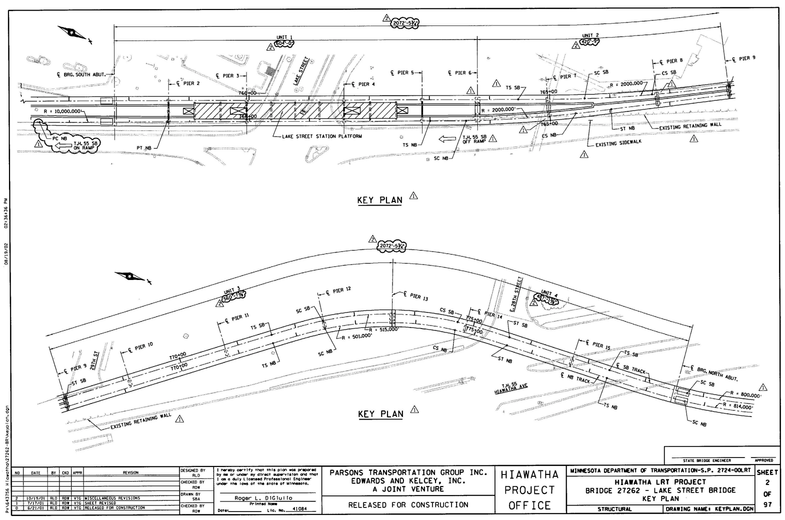
The designer/contractor/owner relationship was crucial on this project and required close contact and quick review times. This required constant coordination so the designer could fully understand the owner's expectations and from that, design a structure that the contractor knew it could build. In this way, everyone's expectations were met. Typical to design-build projects, the plans were issued in work segments as the work progressed. Parsons provided the contractor with just-in-time design plans, releasing only the portion of the design plans the contractor needed at that point. This is a key element in design-build, the work must continually progress from the designer to the owner for review and finally to the contractor in the field. By releasing the plans in defined work segments, the contractor and owner could both focus their efforts on just that portion of work. This reduced the likelihood that unworkable plans and difficult to construct details would be sent to the field. It also reduced the time required for reviews and approvals and allowed the contractor to concentrate its efforts on ordering materials and supplies and organizing its crew. It also allowed similarly used components to be quickly reviewed and approved.

The four-unit structure was issued in three design portions consisting of Unit 4 to the north, Unit 1 to the south and finally Units 2 and 3 in the middle. The foundations, substructure, superstructure, and ancillary elements were issued to the field, as individual progress sets as they were completed in support of the individual segments under construction. This was extremely beneficial in reducing the time required for the review process.

BENEFITS OF POST-TENSIONED CONCRETE

Layout

The geometric layout of the Lake Street Bridge was a major factor in the consideration of bridge types in the preliminary type study phase. Light rail track joins tangent to curved sections of track by using a variable radius curve or spiral. While this allows the LRT vehicle to smoothly move along the track, it can create problems for the fabricator and the contractor on components manufactured in the shop and then field fitted. Cast-in-place concrete is suitable for various alignments, and thus it eliminates many field fit-up problems.



This was especially important for this four-unit bridge which transitions from two single cell box girders at Units 1 and 2 (to allow for the placement of a station platform) to a two cell single box girder in Units 3 and 4. Unit 1, which supports the station, is on tangent track and transitions into a spiral curve after the station ends. Unit 2 geometry was configured to allow the transition to the two cell box by the use of spiral curves, circular curves and tangent sections. Unit 3 and Unit 4 with radii of 501-feet and 800-feet respectively, required the use of material and construction methods that would be efficient yet resist the additional torsional loadings generated by the tight radius.

After preliminary analysis and discussions with the contractor and owner it was determined that cast-in-place concrete was the best material to handle the unique geometry of this structure. It also allowed for the future refinement of the horizontal alignment after the preliminary plans were submitted. More importantly, the box provided the capability of longer spans and shallower depths, thereby minimizing impacts on vertical clearance of roadways underneath. The minimum clear span-to-depth ratio was about 22. The steel plate girder option did not allow engineers the same flexibility and would have required a greater overall superstructure depth. Curved plate girders were not deemed feasible for this structure due to tight radii and economic considerations with respect to span lengths.

Schedule and Cost

As is often the case on design-build transit and highway projects, the bridge is on the critical path of the project schedule. In an effort to minimize both design and construction time, various structure types were considered, such as deck girder structure or curved steel girders. The required tight curvature and long spans meant that tangent girders were not feasible because of the variation in overhang. Cast-in-place post-tensioned box girder was considered the best overall choice. The short lead-time required for this type of structure saved the contractor significant time and money. While the initial material cost for the curved steel girder option was economically comparable, the additional cost associated with raising the track profile and the life cycle cost associated with future maintenance offset any up-front cost saving for this option. Also, the cost/benefit comparison for starting false work and completing the structures early was a very powerful draw for the builder.

The substructure is supported on drilled caissons, using Post-Tensioned (PT) cast-in-place (CIP) concrete allowed the contractor to put "shovel to ground" as quickly as possible once the superstructure box depth was finalized. Through the design quality process, the designers supplied plans to the contractor that allowed it to utilize construction personnel and equipment in the most efficient manner possible.

The CIP box allowed the contractor to forge ahead with caisson and column placement. The box girder was well suited for the complex horizontal geometry, quick to construct, visually pleasing, and low in future maintenance requirements. This all combined to give the best structure for the dollars available. The choice of PT concrete was obvious for this part of the LRT project and allowed a reasonable guarantee there would be no significant changes in the box section should unforeseen design changes occur. Therefore, the substructure design could be advanced and finalized well before the superstructure design was completed.

The comparative cost difference between the cast-in-place concrete box and a steel box structure was approximately $1000 per linear foot or about $40 per square foot resulting in a net estimated difference of 2.1 million dollars.

Design and Constructibility

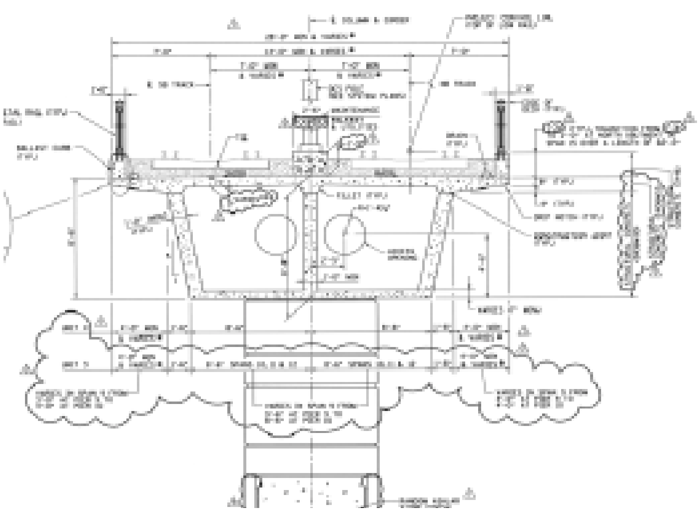
Another major benefit of post-tensioned CIP box girders was their inherent efficiency in handling torsion when compared to the other types of structure. Post-tensioned concrete makes full use of the compressive strength of concrete and tensile strength of prestressing steel, thus giving a very good means for transferring shear to the box web. CIP boxes normally do not see any significant affects due to torsion unless the structure has a small-radius horizontal curve as was the case for these bridges.[3] While the designer did account for web blow out due to prestress force and out of balance live loads, the effects were minimal when compared with what would have been required for the design and detailing of steel girder cross frames. In short, while the structural analysis was detailed and often complex, the final structure was simpler and more efficient than a comparable steel box or plate girder. This translated into a simpler more efficient structure for the contractor to build.

Aesthetically, the box structure had a more fluid and open appearance. It also allowed a structure that would mix well with the surrounding area and not be as obtrusive and bulky as a plate girder structure. A conventional slab-on-plate girder solution would have lead to a deeper structure and would have required a revised track profile with a more intimidating visual effect, thus this solution was not considered efficient or attractive. Also, the PT CIP structure allowed longer spans, thus eliminating piers and impacting the traffic area as little as possible.

The PT CIP structure allowed the project team to minimize structure depth due to the inherent stiffness of this structure type. Through Value Engineering, the box depth was minimized by taking advantage of higher strength concrete and eccentrically balancing the prestress tendons with the applied live and dead loads. This was particularly helpful in Unit 1, where the station loads are carried by the bridge with the help of transverse diaphragms. While the use of concrete increased total dead load to the substructure, temperature effects and thus costs were minimized by the unique moment-reducing hinges used at select piers to minimize temperature effects. The integral casting of piers and superstructure allowed the designer to utilize this cost saving feature.

The cast-in-place box option requires less future maintenance than steel girders would have simply due to inherent properties of concrete. There will be no painting. Minimal bearing and joint repairs will be necessary simply because there are fewer of each for these structures. This is attributed to the moment reducing hinges the project team was able to utilize at select piers. These hinges allowed the designer to keep many of the piers integral and thus allowed a reduction in bearing pads and joints. It should also be noted that the top of column hinges reduced effects from longitudinal temperature and enabled a more efficient and economical substructure to be placed.

The post-tensioning system utilizes 0.6-inch diameter 270 ksi low-relaxation strands in 4 ½ inch diameter ducts with a maximum of 19 strands per duct. The single cell box of Unit 2 and the double cell box of Unit 3 both had four ducts per web and an initial post-tensioning force of 3300 kips per web. The single cell box of Unit 1 with its additional station loads and the double cell box of Unit 4 both had five ducts per web and an initial post-tensioning force of 4000 kips per web. The allowable tension stress was limited to zero psi and the allowable compressive stress was limited to 0.4 fc'.[4] The approved concrete mix design had a 28-day compressive strength of 5500 psi and an initial compressive stress of 4000 psi at stressing. With a maximum unit length of 607-ft and sharp curvature in Units 3 and 4, the units were designed with double end stressing to reduce losses. In addition, Unit 1's post-tensioning was staged to account for station loads to be applied later in the construction sequence.



SUBSTRUCTURE

Large diameter drilled shaft concrete foundations were utilized per the contractor's request, allowing a faster turnaround time than a conventional footing supported on piles. This alternative was even more attractive due to the relatively high elevation of the bedrock, the tight construction area and the use of a single drilled shaft to support each pier. The drilled shafts went in faster and required less overall effort than standard pile and pile cap foundations. The shafts were socketed in the bedrock and are primarily end bearing in the rock. A slurry displacement method was used to place the concrete. This option had the additional advantage of not requiring cross-hole sonic testing due to the end bearing nature of the shafts, the relatively short lengths of the shafts and the quality of the overlying soils.
The caissons also furnished more flexibility when the change from fixed rail to ballasted deck box was implemented. Minimal revisions were required to the caissons, minimizing lost time to the contractor due to this major revision. This is discussed later in the article.

A cost saving design feature was modification of the typical pier configuration from a multi-frame bent on a pile footing foundation to a single column on a large diameter caisson foundation. The pile footing arrangement, though typically economical to construct, did not permit the rapid construction required on this project. Complicated forming and rebar bending details, time intensive pile driving and the impacts a large footing would require were not desirable. Further the large work zone required would unnecessarily restrict traffic flow on the heavily travelled roadways below. The contractor's preference was to use a single large diameter caisson. With this approach the contractor was able to place a large diameter caisson in a 14-foot wide grass median in the middle of busy Hiawatha Avenue with only temporary lane closures and no impact upon utilities. The single shaft caisson was then transitioned directly into a rectangular column with the pier cap cast monolithically with the box structure. This eliminated the need for multiple bearings at each pier. Column sizes ranged from 5'-4" x 9'-4" to 5'-4" x 5'-4" for the double and single cell boxes respectfully.

Drilled Caisson in Median of Hiawatha Avenue (TH-55)

Hinge Reinforcement at Pier

Another interesting feature of the substructure design was the use of a low moment hinge at certain locations. To lessen the effects of temperature, creep and shrinkage forces, the connection at the top of the column was pinned in the longitudinal direction. However, this does not form an actual free pin since a force couple will develop between the concrete and the reinforcement and would be most appropriately thought of as a low moment connection. The designer must calculate demand rotation and provide sufficient gap to allow free rotation for this connection to function properly.

RAIL STRUCTURE INTERACTION

Community interest in this project was high. The original design scheme called for two independent structures separated by a 1200-ft retained fill plug. Well after the foundation and substructure design was complete and the caissons were being installed, the local community and agencies finally weighed in. The community favored a design that provided open spaces and long-spans to one that consisted of a fill embankment that would have created a canyon like feel between the new corridor and an existing elevated roadway, thus creating an open free flowing passageway. The rail structure interaction analysis had been completed when the owner initiated the change to bridge structure. The contractor had purposely not placed the abutment caissons adjacent to the proposed fill section in anticipation of the community's decision to place that portion on structure. Replacing the fill section would be two units comprised of single and double cell box units.

Due to the restrictive track specifications such as allowable rail gap of three inches and zero stress in the rail at 90-degrees Fahrenheit, the rail interaction force under the broken rail condition governed the design of the fixed piers and their corresponding foundation. That was anticipated for Units 1 and 4 where long span lengths were required. The question to be answered was: should Units 2 and 3 continue utilizing the more costly direct fixation track design, or a less costly option such as a ballast track where rail forces are greatly reduced. Preliminary analysis indicated potential problem with a direct fixated track on the now much longer bridge and further analysis was undertaken to determine if the structure would utilize direct fixation track or change to a ballasted track section. After an intensive period of studying the various alternatives, which culminated with a series of meetings in the design office with the owner and the contractor, it was decided to use the ballasted track option, because it was the least disruptive to the schedule, was more economical to construct, and provided a softer riding surface.

The following considerations were given for the use of direct fixation track. Light rail track must remain in tension for its service life. There are two main safety reasons for this: (1) It eliminates the possibility that the track could buckle out of plane during an extreme hot weather event, and (2) if the track were to break, a gap would develop between the free ends of the track. Once the gap develops, a signal interrupt switch senses a loss of continuity in the rail and all train movements are halted until the track can be inspected. The amount of the rail gap is affected by several factors such as the amount of pre-tension in the rail (expressed as the ambient air temperature at zero stress in the rail), the slip-resistance characteristics of the rail fastening device, the unit length, column stiffness, creep and shrinkage. This gap must be maintained to a safe limit to preclude derailment. Direct rail fasteners that connect the rail to the superstructure are available in many different types, such as the spring-clip type proposed on this project. The rail break force will increase until it reaches a limiting value whereby any addition slip would not generate any additional force. Once the decision was made to place the entire area on structure, the fixed rail option became too costly and unyielding, pushing the designer toward a more conventional ballasted box girder structure. Again, the PT CIP box was chosen as the best structure option based on its ability to handle these forces in tension and compression.

CONTRACTOR-REQUESTED CHANGES AND HOW THEY BENEFITED THE PROJECT

Some of the contractor specific changes are due to regional differences and unique local characteristics in Minneapolis and Minnesota. This project has included the Minnesota Department of Transportation (MnDOT) in the review process, and incorporates applicable local standards. Certain standards were not implemented due to the nature of the design-build project. In particular these included standard detailing practices such as layout conventions and bar bend lists typical in MnDOT plans.

As with most design-build projects the relationship between the designers, contractor and owner is critical. On this project, there was open communication between the designers and contractor that allowed for many modifications and adjustments to the plans prior to issuance to the field. These changes could then be brought to the owner for review with a complete understanding of the design and construction issues that were driving them. In addition, the project QA/QC process specifically included a contractor multidisciplinary review and resolution prior to owner review, which always provided the team with a better product with the least amount of delays, rework, and change orders.

The post-design process included the use of “Field Design Memorandums” (FDM), which allowed the contractor to request a field change to the issued plans. Field changes were typically based on changed field conditions, construction methods, vendor supplied material incorporation, or construction inaccuracies. This process allowed the contractor and engineer to work together to define, solve and draft an FDM acceptable to the team. The owner typically was included or informed of the pending FDM depending on its magnitude. The FDM was then processed through the QA/QC coordinator for consistency.

Other contractor requested changes were due specifically to the nature of the design or related to the construction methodology. The contractor requested many design changes and modifications during the design review process. These were not processed as change orders, but rather were documented in the review process and issued to the field. Changes to previously issued sets based on review comments to new segment work were processed through both the FDM and “Request For Revision” (RFR-Design instituted changes) procedures. Specific changes, FDM’s, and RFR’s are described below.

Change from pile supported footing to single large diameter shaft foundations. This allowed for a more efficient and quicker construction and was a type of foundation the contractor was very familiar with. This also allowed for a single column configuration rather than a multiple column pier. This in effect reduced the overall construction impact area on the project.

Another revision requested by the contractor was the use of black versus epoxy bars. Standard practice for the State of Minnesota is to utilize epoxy coated reinforcing bars (rebar) for all substructure and superstructure elements. Because the concrete box girder is much more rebar intensive than other structure types and because a well defined path needed to be established for stray current protection, the contractor requested the use of additional concrete cover in lieu of the more expensive epoxy coated rebar. This created some design challenges, especially in the girder webs, in order to allow for the post-tensioning ducts and reinforcement. The additional dead load added by thickening the various components was not significant and was justified by the cost savings realized by substituting the black bars. It should be noted this change did not affect long-term serviceability or reduce expected life of the structure.

The contractor requested the use of MSE walls in lieu of the standard cantilever walls for the bridge approaches. This wall type was much more cost effective and quicker to construct than the standard wall type proposed. The owner was at first reluctant to use this concept stating durability concerns. However, after discussions with the designers and vendors the owner’s concerns were alleviated and the cost savings realized.

The original proposal also called for the use of modular joints for the box girder structure. Due to the change to ballasted track, the contractor requested that a plate and waterproofing system be substituted in lieu of the modular joint system originally proposed. The final design accommodated this request allowing a practical solution at a lower cost and minimizing future accessibility concerns with respect to the ballast and track ties on the bridge.

Stray current issues required the use of bonded reinforcement at certain location throughout the bridge. While the bonding of stray current is not typically categorized as rebar welding, the owner required that all reinforcing steel that is to be welded (including stray current welds) be A706 bars per AWS 1.5. In an effort to reduce cost, the contractor proposed welding only the ends of the standard A615 bars and using the A706 bars only where end welds could not be done. In this way, the contractor reduced both the overall number of welds and minimized the use of the more costly and less available A706 steel.

CONCLUSION

The Lake Street Bridge was an ideal use of post-tensioned concrete. It has a comparative initial cost to other structure types and low long-term maintenance cost for the owner. It allowed for complex horizontal geometry, and a tight construction schedule. An additional benefit was the contractor familiarity with this type of construction and the relative short lead-time required, yielding the maximum flexibility to the schedule. Aesthetically, this structure has smooth clean uniform line, pleasant to look at, and provided the open appearance the local community and owner desired.

Unit 4

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