# DESIGN OF A PRECAST CONCRETE ARCH FOR THE FULTON ROAD BRIDGE REPLACEMENT

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## ABSTRACT

The Fulton Road Bridge is a 75-year old cast-in-place open-spandrel concrete deck arch located in a culturally significant section of Cleveland, OH. The bridge crosses directly above the Cleveland Metroparks Zoo, northeast Ohio's largest zoo attended by over a million visitors annually.

Because of the bridge's prominent location and the community's enduring connection to the existing arch bridge, the Cuyahoga County Engineer's office requested a replacement bridge with a similar arch-type structure. The replacement bridge will consist of six 210-foot precast concrete arch spans, to approximately match the geometry and appearance of the existing bridge. Each span will have four lines of arch ribs. Each precast arch rib line will be fabricated in three segments, and will be spliced with post-tensioning.

The use of precast arch rib segments to minimize the need for scaffolding and formwork supported in the zoo is described in this paper, as well as specialized construction methods to optimize the design and minimize negative impact below the structure. The paper also focuses on unique design challenges associated with post-tensioning and erecting the arch ribs for this replacement structure.

**Keywords:** Concrete Arch, Precast Segmental Concrete, Post-Tensioning

## INTRODUCTION

The Fulton Road Bridge, in Cleveland OH, is a seventy year old concrete arch bridge that for many years has carried a significant volume of traffic 100-ft above the Cleveland MetroParks Zoo, Brookside Park, Big Creek, and two active railroad lines. Replacement of this concrete open-spandrel deck arch bridge, which was constructed in 1932, has become imperative because of its severely deteriorated condition.

Because of its location inside the Cleveland MetroParks Zoo, which is patronized by over a million visitors yearly, the bridge has long been a highly visible structure and an important symbol to the community. The bridge is also one of the few of its type and era still in use in Ohio. For this reason, great care has been taken to solicit and implement feedback from stakeholders and the public to fully appreciate and understand the context of the bridge site. A bridge alternative study has been performed to evaluate replacement bridge types, focusing on maintaining the unique character and significance of the structure and minimizing negative impacts to the Zoo, in the spirit of context sensitive design.

After evaluating a number of conceptual and preliminary bridge replacement types, three feasible alternatives were advanced for more detailed study and presented in a public forum. Based on preliminary engineering and public input, a precast concrete arch alternative, with six 210-foot spans to resemble the existing structure, has been selected and advanced to final design, which is currently ongoing. Final design has incorporated design solutions and construction methods that best address the unique context of the bridge and its site. Parabolic arch rib segments will be fabricated in approximately 59-ft, 70-ton pieces, and erected using stays supported on the pier columns. This top-down approach to the arch construction will minimize the negative impact to the Zoo and the railroads.

## PROJECT BACKGROUND

The conceptual design phase followed a number of previous efforts to address concerns with the deterioration of the bridge. These concerns are of particular importance in light of the significant pedestrian traffic that passes beneath the structure. The conceptual design effort also encompassed a number of environmental, cultural and historic issues associated with the replacement of the structure.

### EXISTING BRIDGE

The Fulton Road Bridge was constructed in 1932 and consists of six 210-foot concrete open-spandrel cast-in-place deck arch spans and concrete approach spans. The overall length of the bridge is approximately 1,600 feet. Four lines of arch ribs support the deck, which is a flat-slab that is integral with the

Fig. 1 Existing Fulton Road Bridge (1932 and Today)

spandrel columns. The structure carries four lanes of vehicular traffic over the Cleveland Metroparks Zoo, Big Creek, John Nagy Boulevard, and the Norfolk Southern and CSX railroad lines. As a result of the structure's age and long-term exposure to deicing chemicals, significant deterioration has occurred, including moderate to severe spalling of concrete and exposure and corrosion of reinforcing steel. Because of the extensive nature of the deterioration in the structure, rehabilitation of the structure was not judged to be a practical alternative.

ENVIRONMENTAL, CULTURAL AND HISTORIC ISSUES

The existing bridge crosses over the Cleveland MetroParks Zoo and is very visible from Brookside Park, Interstate I-71, and Pearl Road. The Zoo annually takes in more than one million visitors, and the bridge has become an enduring symbol for the area. The cast-in-place deck arches comprising the structure give the bridge a unique appearance that is considered very desirable to maintain in this prominent site.

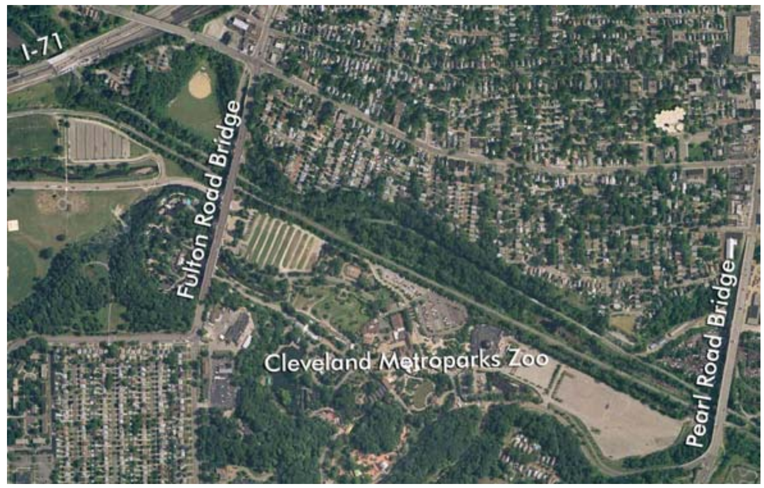

Fig. 2 Fulton Road Bridge Site

Because of the significance of the existing structure and sensitivity of the bridge site, a considerable effort was undertaken to identify environmental, cultural and historic issues. The following list summarizes key issues:

- <u>Brookside Park Bridge under Fulton Road Bridge</u> – The Brookside Park Bridge is a three-hinged concrete arch which was constructed almost 100 years ago (1909) and currently carries pedestrian traffic in the Zoo directly under the Fulton Road Bridge. This structure is on the Ohio Historic Bridge Inventory and must be protected during removal of the existing bridge as well as construction of the new bridge.

- <u>Big Creek</u> – Big Creek runs directly under the Fulton Road Bridge and flows nearly parallel to the alignment of the bridge near its center spans. The creek will affect access to certain portions of the bridge during construction, and its presence will affect the means available to the contractor for construction and demolition.

- <u>Stakeholder Preference / Public Input</u> – Because of the sensitive nature of the bridge replacement, receiving input from the public and key stakeholders was critical to successfully identifying a preferred replacement alternative.

- <u>Railroad Coordination</u> – The Fulton Road Bridge crosses over two sets of tracks near the north end of the bridge. These tracks are operated by CSX and Norfolk Southern.

Measures will need to be taken during construction to ensure that negative impact to the operation of the railroads is minimized and to ensure that the tracks are not damaged during demolition or construction.

- Zoo Operations – Portions of the bridge are in close proximity to animal enclosures and other Zoo facilities, and pedestrian trails are located directly under two spans of the bridge. Noise, vibration and reduced air quality from demolition and construction, as well as limitations on access to portions of the Zoo during construction, have potential for negative impact on Zoo operations.

## GEOMETRIC REQUIREMENTS

The issues described above helped to establish geometric constraints for the new replacement bridge and provide the basis for the context of the bridge site. These general parameters included the overall form of the bridge, the span lengths, pier locations, and clearance limitations. Specifically, the following geometric parameters were decided upon at the outset of the preliminary design after careful consideration of the key issues described above.

- Because of the strong sentiment and personal attachment to the existing arch bridge, it was decided prior to the development of alternatives that the new bridge would be “arch-like” in appearance.

- Similarly, because of the appeal of the existing structure’s appearance, it was decided that a dramatic change in span lengths from the existing 210-foot spans would not be desirable. More importantly, to limit the impact to the Zoo and Brookside Park as described above, and to minimize right-of-way acquisition, it was deemed important to maintain piers at the existing pier locations.

- The presence of the two railroads at the north end of the structure introduced vertical clearance requirements that affected the permissible structure depth at this location. Since the bridge is very high over the valley, this would not prevent the use of normal structure depths for typical multi-girder structures; however it does have an impact on the geometry of supporting arch ribs for deck arch structures.

These geometric parameters, established early in the conceptual design, provided a context for the development of bridge replacement alternatives and put practical limitations on feasible replacement types. It was also determined at the outset of the project that the new bridge would be placed on the same alignment as the existing bridge, and that the existing bridge would be taken out of service during construction and traffic detoured around the site for the full construction period (approximately 2 years). By establishing these parameters early, the determination of the preferred bridge replacement type was facilitated by eliminating some inappropriate structure types at the beginning of the process.

## CONCEPT DEVELOPMENT

The development of appropriate concepts for the replacement of the Fulton Road Bridge was carried out in a systematic process whereby the design team started with a wide range of possible structures, and in a step-by-step fashion, narrowed the options to a final preferred alternative. The process of eliminating concepts and determining a final preferred alternative was performed by measuring alternatives against a well-defined set of evaluation criteria, which were weighted on the basis of perceived importance and impact on the overall success of the project. A straightforward evaluation matrix was developed to rank alternatives in a quantitative fashion and to determine three feasible alternatives, which were then further developed from an engineering design standpoint and subsequently formally presented to the public for open selection.

### CONCEPT PRESELECTION

With the goal in mind of replacing the Fulton Road Bridge with another structure “arch-like” in appearance, the design team initially developed twelve different alternatives for the bridge replacement. Each of these alternatives fit the criteria of being “arch-like” in appearance, even though several were not true arch-type structures.

Each concept was evaluated on the basis of the following preliminary criteria:

- Construction Impact
- Aesthetics
- ‘Arch-type’ Conformance
- Maintenance
- Initial Cost
- Life Cycle Cost
- Arch Demolition Required
- Use of Existing Foundations
- Conventional Construction Methods
- Construction Schedule
- Stakeholder Preference

Each of the preliminary criteria was treated with equal importance in this stage of the selection process, and the evaluations of the preliminary bridge alternatives were subjective on the basis of their favorability against these criteria. This subjective, non-quantitative evaluation allowed for the elimination of several concepts and the definition of preliminary alternatives for further development.

## DETERMINATION OF FEASIBLE ALTERNATIVES AND PREFERRED ALTERNATIVE

Based on additional engineering and analysis of the preliminary alternatives, the design team determined three feasible alternatives that best met the following objective criteria:

- Aesthetics - For the reasons of visibility and cultural significance, global aesthetics was a very important criterion for evaluating the bridge concepts.

- Stakeholder Preference - This criterion is a measure of the reaction of stakeholders to the appearance of the structure and an assessment of the extent to which the public could be expected to accept and embrace the bridge. It is also a reflection of the extent to which the new structure met the standard of being an “arch-like” structure.

- Initial Cost - This criterion is an evaluation of the estimated initial cost of construction for each alternative. Initial cost estimates were approximate at this stage of the conceptual bridge type evaluation, and were based on approximate structural quantities that had been determined from preliminary engineering analysis.

- Construction Impact - This criterion evaluated the extent to which construction would result in significant temporary or permanent impact on the surroundings, including the Metroparks Zoo and the railroad lines beneath the bridge.

- Constructability - Each alternative was evaluated on the basis of the ease of construction, the extent to which complexity and the potential for delays or problems in construction were minimized, and the extent to which the alternative would maximize the use of local labor and materials.

- Future Maintenance and Life-Cycle Costs - Future life-cycle costs refer to expenses that recur over the life of the structure that are necessary to maintain the functionality, serviceability and safety of the structure.

Each criterion was assigned a weight factor in relation to its perceived relative importance. An overall score for each alternative was then calculated based on the sum of the ratings multiplied by the weighting factor. In this manner, three feasible alternatives were identified:

<u>Feasible Alternative A - Precast (Contemporary) Concrete Arch</u> – This alternative is a precast concrete arch bridge with 210-foot long main arch spans similar to the existing structure. This alternative employed the use of modern materials and construction methods with four spandrel columns in each span, giving more open space and a more contemporary appearance than the existing bridge.

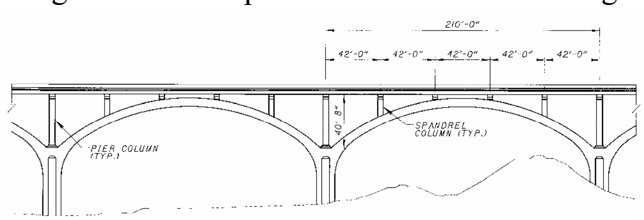


Fig. 3 Precast (Contemporary) Concrete Arch

Feasible Alternative B - Precast (Traditional) Concrete Arch – This alternative is intended to match, as closely as possible, the appearance of the existing bridge. A cast-in-place concrete deck arch similar to the existing bridge evaluated very positively compared to other alternatives, primarily on the strength of its aesthetics and on the basis of stakeholder preference. Recognizing the impact that the formwork required for a cast-in-place solution would have on the park and zoo, this alternative attempted to recreate the appearance of the existing bridge with precast rather than cast-in-place elements.

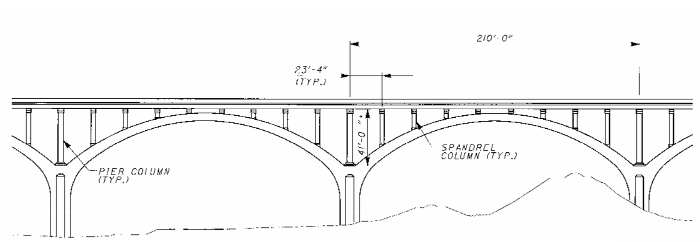


Fig. 4 Precast (Traditional) Concrete Arch

Feasible Alternative C - Concrete Delta Frame – The third feasible alternative was a precast concrete delta frame bridge with 210-foot long main spans. This alternative represents a more significant visual departure from the existing bridge than Alternatives A and B. The delta frame was made to appear more 'arch-like' by increasing the curvature of the supporting legs at the piers. The resulting structure provided a more modern-looking appearance with increased open space between spans and a more streamlined appearance to the bridge.

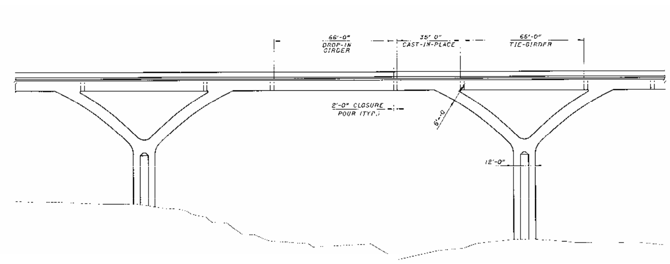


Fig. 5 Concrete Delta Frame

At the conclusion of a final public meeting and after all comments were received from the public, the Contemporary Concrete Arch alternative was selected as the preferred alternative. This selection was based on the preference of the public, in addition to slightly lower cost and expected construction duration in comparison to the other alternatives.

Fig. 6 Rendering of Contemporary Concrete Arch Preferred Alternative

**FINAL DESIGN**

The selected alternative consists of six 210-foot concrete arch spans with a rise of 41'-8" from spring line to crown. Four lines of precast arch ribs, spaced at 21-foot centers, are used in each span, similar to the existing structure. Each line of arch ribs consists of three precast arch segments per span to minimize negative impacts to the site and facilitate ease of construction. The overall width of the new structure will be 82-ft, which will accommodate four lanes of traffic, two 5-ft wide bike lanes, and two 10-ft wide shoulders. The superstructure will be comprised of standard prestressed I-girders, which will be supported on elastomeric bearings at each spandrel column, and a conventional cast-in-place concrete deck.

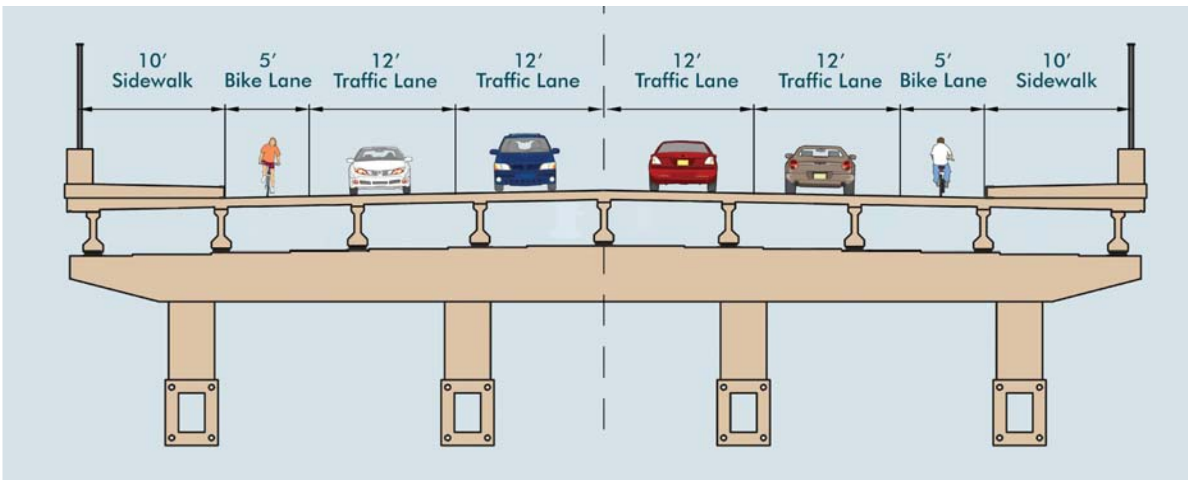


Fig. 7 Representative cross-section of the proposed structure

Challenges associated with the final design of the structural concept selected include the post-tensioning design for the arch ribs, slenderness considerations, determination of an appropriate construction scheme, and selection of appropriate analysis methods.

ARCH POST-TENSIONING

Post-tensioning of the precast arch ribs is required to meet the stress requirements of segmental construction. The use of post-tensioning in an arch may seem counterintuitive, because arches are commonly regarded as carrying loads in axial compression with little bending. Tensile stresses in the Fulton arches, however, are of sufficient magnitude to require the use of post-tensioning. The post-tensioning design is best understood by first examining arch behavior and the factors that give rise to the large tensile stresses in the Fulton arches.

The transmission of load though an arch as axial compressive force is often termed *arch action*. The development of moments in structures under loads is, by contrast, termed *beam action*. The degree of arch action and beam action in arches with equal spans and cross-sections is influenced by the geometric profile of the arch rib, the fixity of the arch springline, and the arch construction procedure. The assumption that an arch is under compression for dead and live loads is most appropriate for arches that follow a geometric profile, termed the line of thrust, which balances the compressive dead load forces at each spandrel joint. When an arch follows the line of thrust, the dead load compressive forces in the spandrel and arch rib above the joint sum to a wholly compressive force in the arch rib below the joint. For an arch supporting spandrel columns, the line of thrust is a polygon with vertices at the intersections of the rib and spandrel columns[1]. Although elastic rib shortening of arches will induce moments due to dead load, these moments are generally small in magnitude for arches that follow the thrust line[1]. Beam action tends to increase, however, in arches that do not follow the line of thrust.

For a structure to be classified as an arch, horizontal reactions must be developed by both end supports at the springline[1]. Otherwise, the structure will be incapable of transmitting any load through arch action. In general, if the horizontal springline supports are capable of yielding, arch action will decrease and beam action will increase. Horizontal support flexibility develops if the foundation material is not fully rigid or if the arch is placed on piers.

Arch ribs are traditionally cast-in-place on falsework, which allows the structure to carry self-weight loads through arch action when the falsework is removed. When an arch is constructed incrementally, however, larger moments due to self-weight may be locked into the arch than if the entire arch was constructed on falsework. The arches of the proposed structure will deviate slightly from the line of thrust, rest on support piers that are founded on yielding foundations, and will be constructed incrementally from precast segments. Taken together, these factors all increase beam action and decrease arch action, and give rise to large tensile stresses in the arch ribs for combined dead load plus live load.

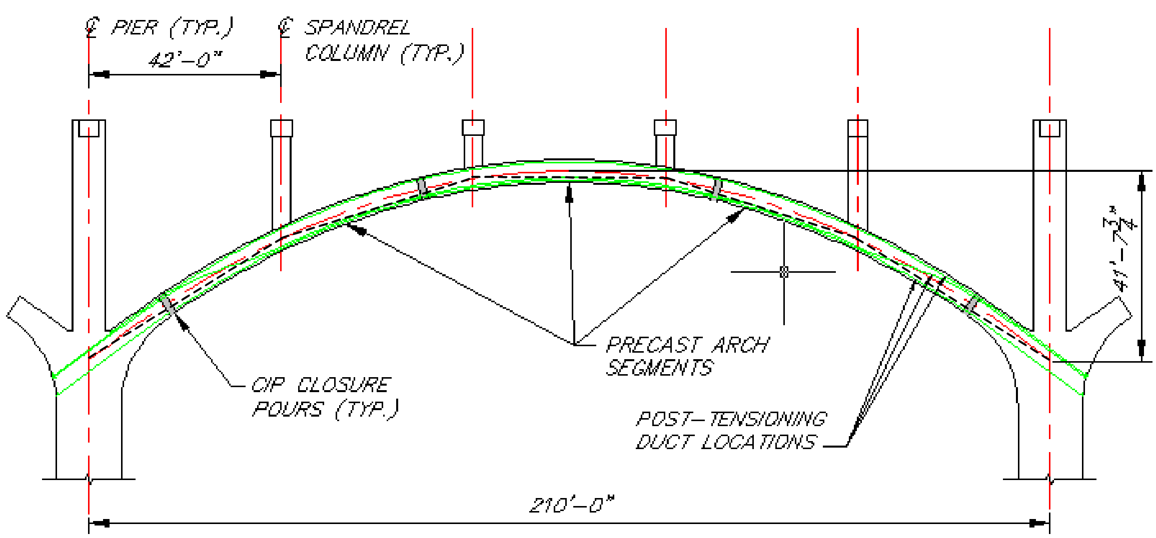


Fig. 8 Typical arch geometry and segment layout for the new Fulton Road Bridge. The line of thrust for the dead loads of the structure is shown superimposed on the proposed arch with dashed lines.

The individual effects of arch geometry, flexible supports, and construction sequence on the behavior of the proposed structure may be examined by comparing the axial forces, moments, and stresses of five example arch structures. Each arch has the same span, spandrel column spacing, and cross-section as the proposed structure. Arches One through Five are loaded with the self-weight and superstructure dead loads of the proposed structure, which are superimposed with a half-span AASHTO HS25 lane loading with a distribution factor of two. The superstructure dead loads and half-span live loads are shown on Arch One in Fig. 9 and Fig. 10, respectively.

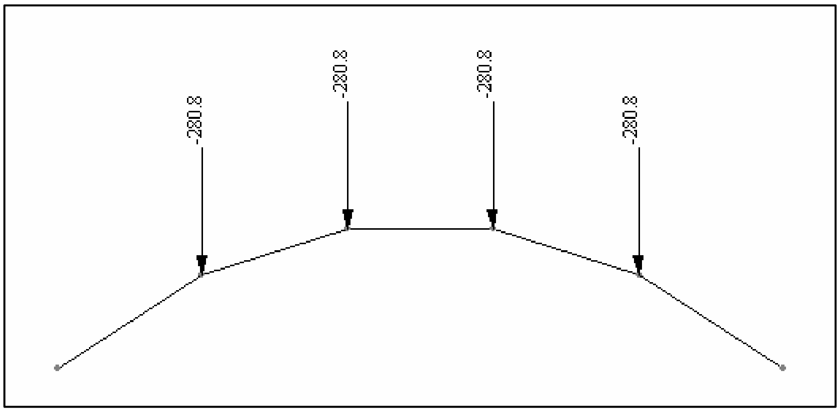


Fig. 9 Superstructure dead load (in kips) on Arch One. The same loads are applied to parabolic arches Two through Five.

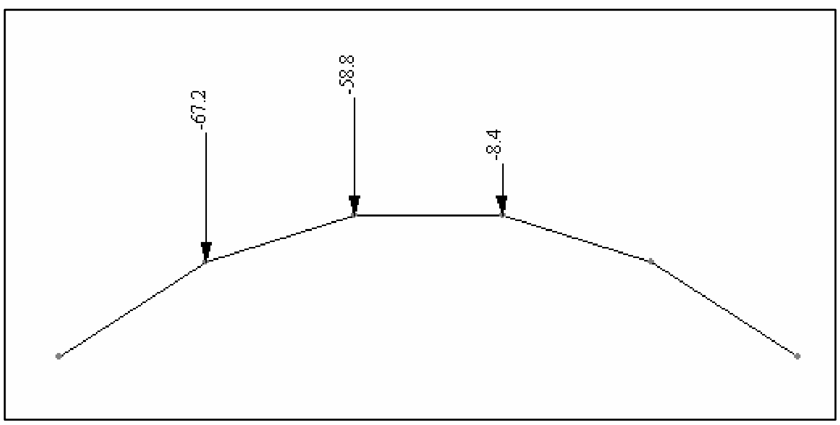


Fig. 10 Half-span AASHTO HS-25 live load (in kips) on Arch One. The same loads are applied to parabolic arches Two through Five.

Arch One is a polygonal arch with a rise of 40-ft, and follows the line of thrust derived for the proposed superstructure dead loads. The springline supports of Arch One are fully fixed and unyielding. Arch Two is a parabolic arch with the same profile as the proposed Fulton arch. A parabolic arch profile is proposed to keep the arch geometry as close to the line of thrust as possible while satisfying the community's desire for a structure that closely resembles the arches of the existing bridge. This profile follows the line of thrust closely by passing through the vertices of the thrust line at the joints between spandrel columns and arch rib. The supports of Arch Two are fully fixed and unyielding. Arches Three through Five have the same profile as Arch Two. Arch Three is supported on the piers of Span 4 of the proposed structure. The bases of the piers supporting Arch Three are fully fixed and unyielding. Arch Four has the same configuration as Arch Three, except the pier bases of Span 4 are supported on foundation springs to model the spread footings of the piers on shale. Arch Five is the same as Arch Four, except for the addition of the locked in dead loads from the proposed construction sequence. Arches One through Four are cast-in-place. Creep and shrinkage effects are neglected to simplify the comparison.

The axial forces in each structural system are shown in Fig. 11. As expected for arch behavior, the axial forces are wholly compressive. The axial forces in fixed springline Arches One and Two are approximately equal in magnitude along the arch span. Compressive axial forces decrease in Arches Three and Four as the supports are made more flexible, but increase somewhat when the construction sequence is taken into account in Arch Five. The Arch Five compressive axial forces are nonetheless smaller in magnitude in the middle three-fifths of the span than the forces for arches fixed at the springline. The quantity of arch action thus seems unaffected by the deviation of the proposed structure's parabolic arch profile from the true line of thrust, but decreases as the supports are made more flexible by the use of piers and foundation springs.

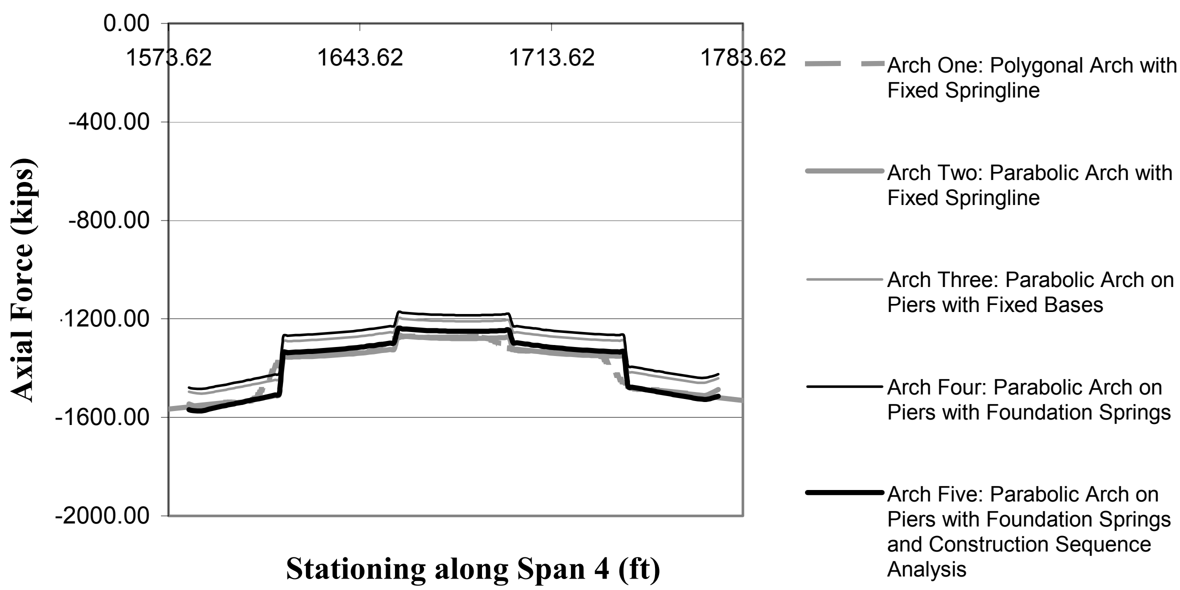


Fig. 11 Axial forces in Arches One through Five for dead load plus half-span HS25 live loads. Compressive forces are negative. Tensile forces are positive.

The moments in Arches One through Five are shown in Fig. 12. There is significant variance between the moments for Arches One and Two, which are both fully fixed at the springline. The maximum positive moment in Arch Two is roughly twice the magnitude of the maximum positive moment in Arch One. Since Arch One is polygonal and follows the line of thrust, and Arch Two is parabolic and deviates slightly from the thrust line, the deviation of the geometric profile of the proposed Fulton arches from the line of thrust has a significant effect on increasing the quantity of beam action in the proposed structure. The maximum magnitudes of positive and negative moments increase further in Arches Three and Four as support flexibility increases. The use of piers instead of fully fixed supports causes the largest increase in beam action. The addition of construction sequence effects in Arch Five slightly decreases positive moments under the spandrels and increases negative moments near the supports. The effects of long-term creep, however, tend to shift the moment diagrams of structures built sequentially towards those of otherwise identical structures cast-in-place at one time. The moment diagram of Arch Five will over time approach the moment diagram of Arch Four. The quantity of beam action in the proposed structure is therefore increased by the deviation of the proposed structure's parabolic arch profile from the true line of thrust, the increased support flexibility from the use of piers and foundation springs, and the construction sequence of the proposed structure.

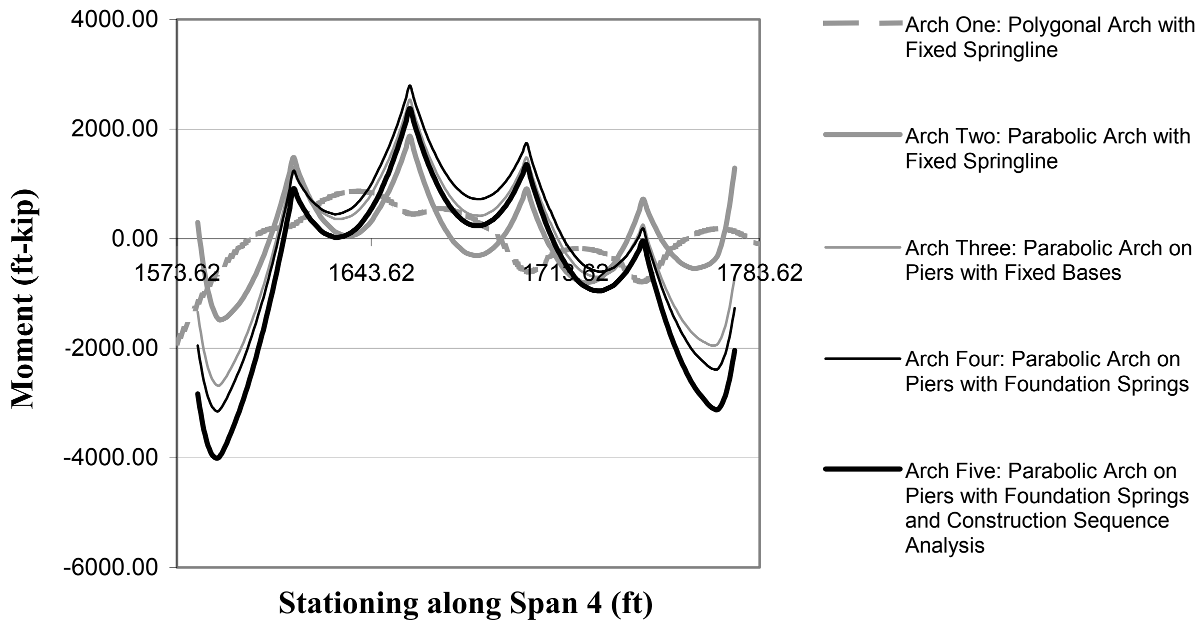


Fig. 12 Moments in Arches One through Five for dead load plus half-span HS25 live loads. Positive moments create tension on the bottom face of the arch. Negative moments create tension on the top face of the arch.

The development of tension in the arches of the proposed structure can be seen most clearly through the use of stress plots for Arches One through Five under the combined dead load and half-span live loading. The stresses at the top and bottom faces of Arches One through Five are shown in Fig. 13 through Fig. 17, respectively. The limiting service load tensile stress for the precast arches with 7000 psi concrete is $6(f'_c)^{1/2}$ = + 502 psi, while the limiting service compressive stress is $0.60\, f'_c$ = - 4200 psi. These stress limits follow the requirements of the AASHTO *Guide Specifications for Design and Construction of Segmental Concrete Bridges, Second Edition 1999*[2], for segmental structures with sufficient bonded reinforcement to resist the total tensile force in the closure joints.

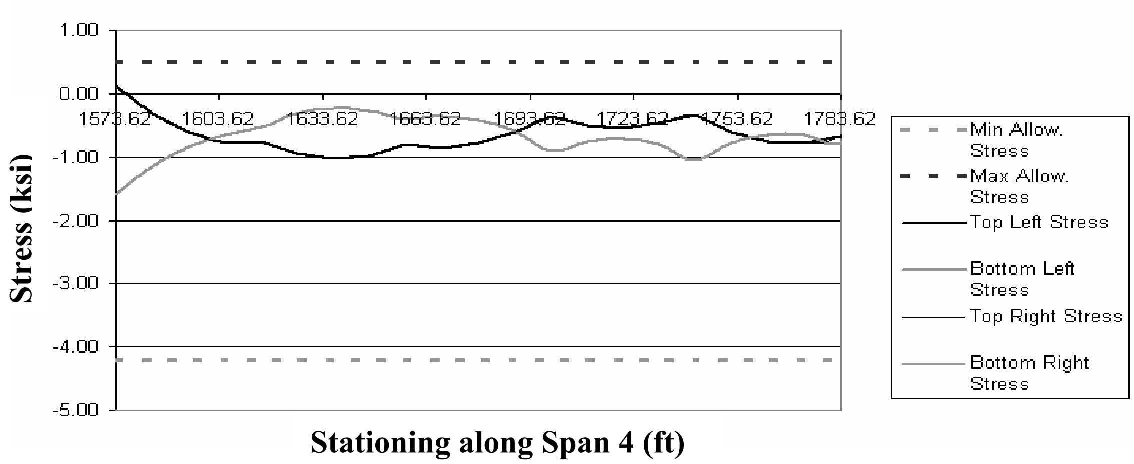


Fig. 13 Stresses due to dead load plus half-span live load in Arch One: Polygonal Arch with Fixed Springline. Tensile stresses are positive, compressive stresses are negative.

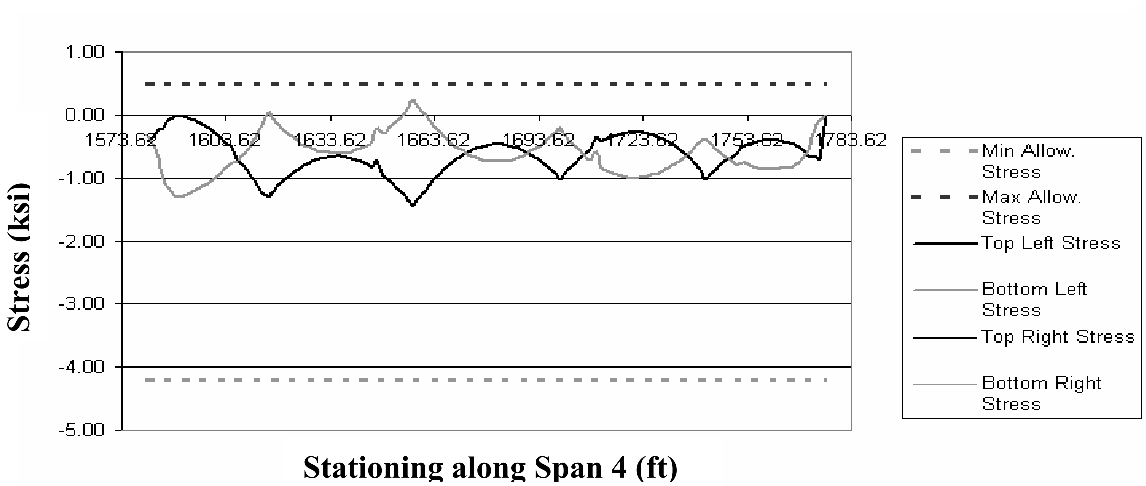


Fig. 14 Stresses due to dead load plus half-span live load in Arch Two: Parabolic Arch with Fixed Springline.

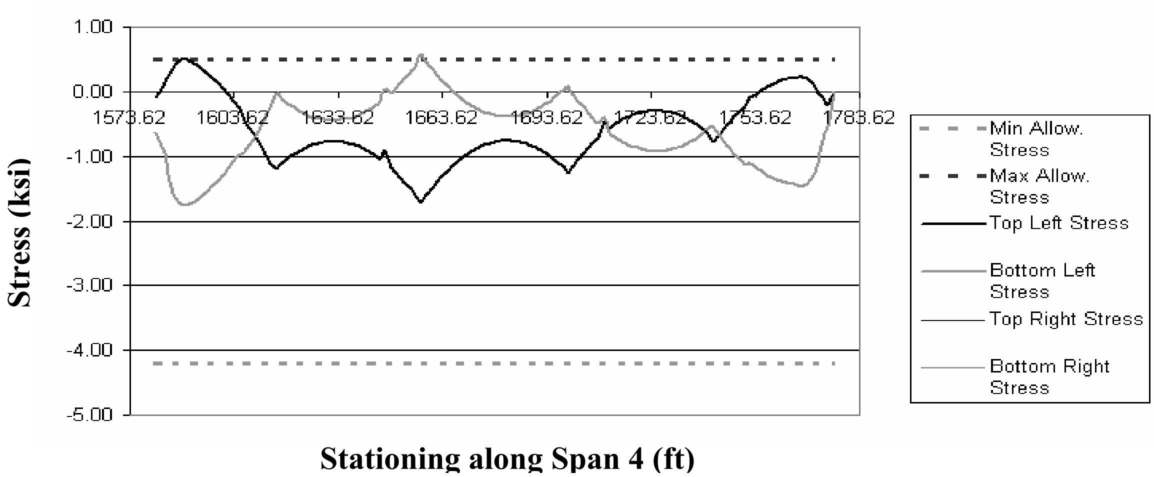


Fig. 15 Stresses due to dead load plus half-span live load in Arch Three: Parabolic Arch on Piers with Fixed Bases.

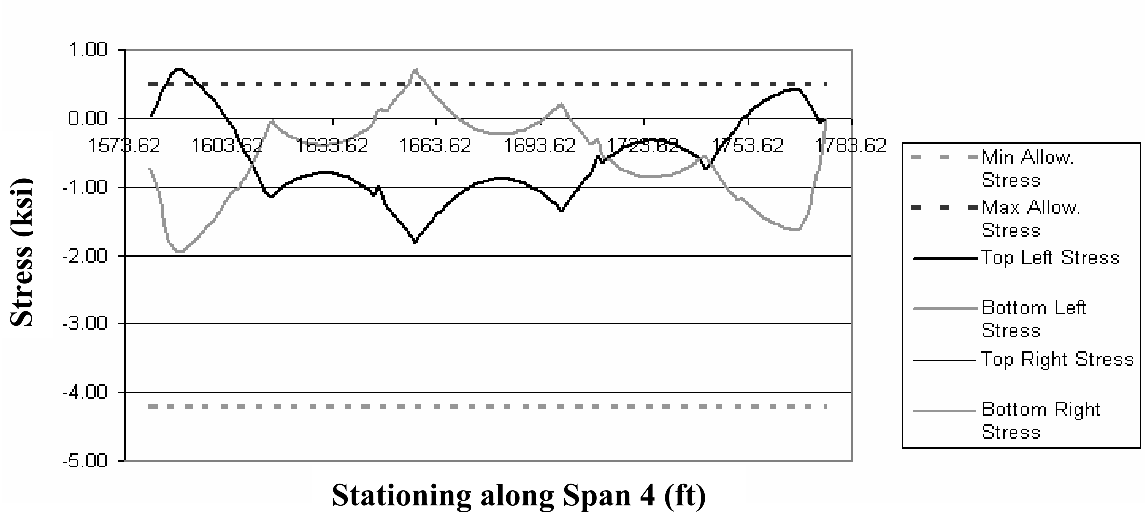


Fig. 16 Stresses due to dead load plus half span live load in Arch Four: Parabolic Arch on Piers with Foundation Springs.

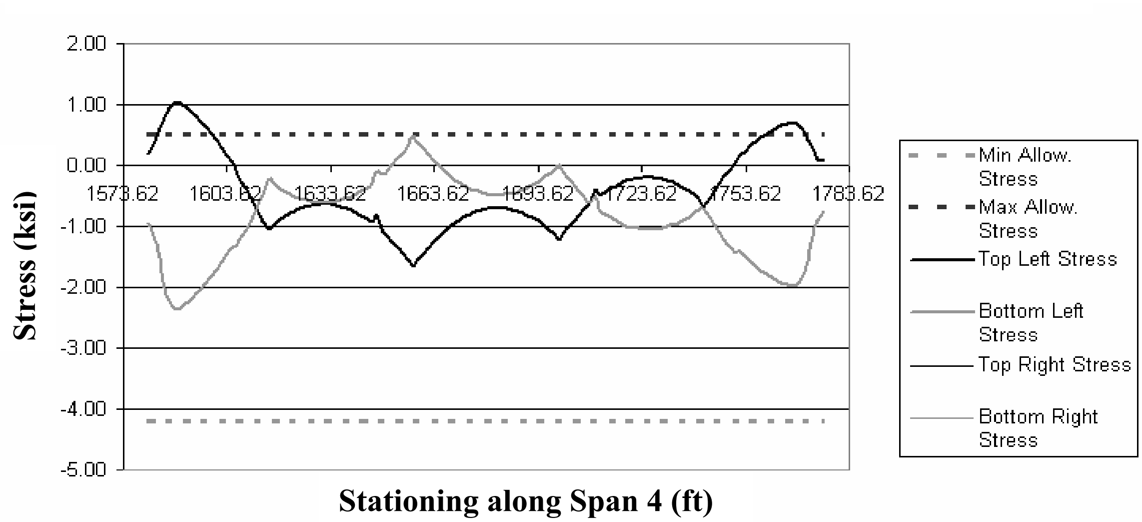


Fig. 17 Stresses due to dead load plus half span live load in Arch Five: Parabolic Arch on Piers with Foundation Springs and Construction Sequence Analysis.

The plots show tensile stress increasing in Arches One through Five from virtually no tensile stress in Arch One, to a maximum tensile stress of nearly 1.00 ksi in Arch Five. The slight deviation of Arch Two from the thrust line is sufficient to noticeably increase the tensile stress in Arch Two in comparison to Arch One. Placing Arch Three on piers, in comparison to the fixed supports of Arch Two, causes a further increase in tensile stress. Adding foundation springs to the piers causes tensile stresses to increase noticeably above the limits of the AASHTO *Guide Specifications* for Arch Four. Accounting for the construction sequence of Arch Five causes tensile stresses to increase further in the negative moment region near the springline, and to decrease slightly in the positive moment regions under the spandrel columns. Through moment redistribution due to creep, the stress plot for Arch Five would be expected over time to approach that of Arch Four.

Several conclusions can be drawn from the stress comparison of Arches One through Five. Since Arch Five has geometry, supports, and a construction sequence identical to that of a typical span of the proposed structure, it is clear that the proposed Fulton Road Bridge precast arch ribs require post-tensioning to satisfy the stress limits of the AASHTO *Guide Specifications*. Secondly, since the tensile stresses increase gradually from Arches One to Five, the high tensile stresses in the arch ribs of the proposed structure are induced by a combination of geometric profile, support flexibility, and construction sequence causes. Taken alone, neither the deviation of the parabolic arch profile from the thrust line, the flexibility of the arch piers and foundations, nor the construction sequence would likely be sufficient to induce tensile stresses that require post-tensioning of the arch rib. Lastly, it is informative to note that many cast-in-place concrete arch bridges built during the first half of the twentieth century closely followed the line of thrust and were founded on fixed supports, giving these structures a configuration similar to that of Arches One and Two. From the low tensile stresses present in Arches One and Two, it can be inferred that many traditional cast-in-place arch structures are inherently prestressed by carrying live loads and the dead load forces of the arch rib, spandrel columns, and superstructure in nearly pure compression. These bridges were thus efficient structures in an era when labor was cheap and prestressing technology was in its infancy.

## POST-TENSIONING LAYOUT

Post-tensioning is proposed to economically provide strength for the increased moments in the arch. The ends of the arch ribs near the fixed supports are regions of large negative superimposed dead load and transient load moments. Large positive moment peaks arise at the junction of the arch ribs and spandrel columns. At first glance, the simplest post-tensioning scheme for the arch ribs would be to use continuity tendons extending over the entire length of each rib. These tendons would be deviated towards the top of the rib near the fixed supports, and towards the bottom of the rib under the spandrel columns. The beneficial

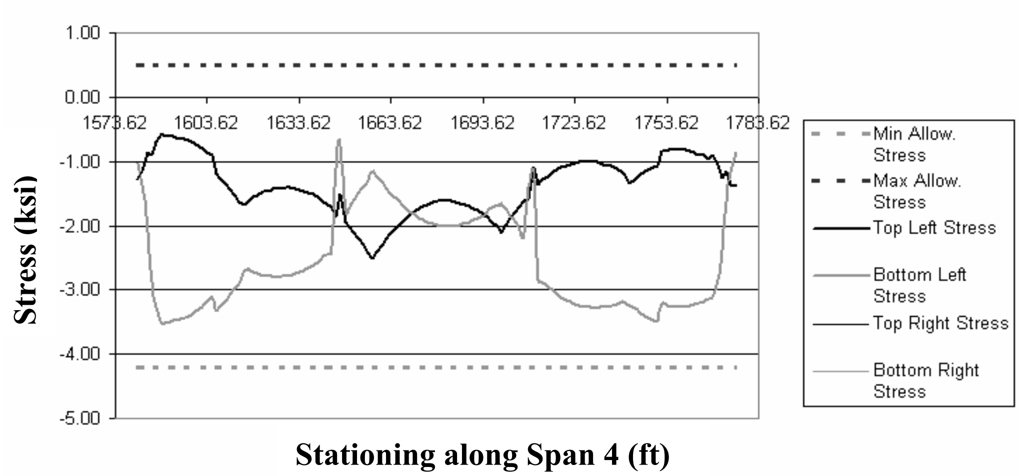


Fig. 18 The stresses resulting from the superposition of Span Four post-tensioning forces with the dead load and half-span live loading of Arch Five.

primary moments of this scheme, however, are completely counteracted by secondary prestress moments that arise due to the restraint of the fixed supports of the arch. Primary prestress bending moments cannot be induced in a curved beam with fixed supports through post-tensioning[3].

Eccentric post-tensioning can be used with greatly reduced secondary moments, provided that it is stressed before the segments are spliced together into a continuous arch. The post-tensioning scheme proposed for the new Fulton Road Bridge places eccentric tendons in the regions of highest moments. The end segments will be installed first and eccentrically post-tensioned to the pier bases. The middle segment will be eccentrically post-tensioned before installation into the arch rib. Once closure has been made between all three segments of the arch rib, concentric continuity post-tensioning will be stressed from end-to-end of each arch. Continuity tendons placed in a curved beam of constant radius with fixed ends produce constant radial forces, which generate only constant normal forces in the beam, and no bending moments[3]. If the radius of the beam is not constant, the radial forces change their value and direction, and secondary prestress moments are induced[3]. Some secondary moments will arise from the continuity tendons used in the proposed structure due to the variable radius of the parabolic arch, and the deformations of the arch structure. These secondary prestress moments are relatively small, and are comparable to the secondary moments that would be expected in a post-tensioned continuous beam design.

The proposed post-tensioning scheme allows for simple stressing of tendons by having all jacking operations occur at the pier bases of the arch rib or in the casting yard. Detailing and construction of the precast arch rib segments is simplified by avoiding the use of tendon anchors in intermediate locations along the segments. Instead, all anchors are located either in the pier bases or at the ends of the segments. The precast segments are solid at their ends and under the spandrel columns, and are hollow elsewhere to conserve material and allow for economical transport and erection.

## SLENDERNESS DESIGN

The moment magnification procedures of AASHTO are primarily intended for frame structures, and careful attention is required for proper application to arch rib design. Second order moments are determined in AASHTO by magnifying the first order frame end moments. This approach is not well suited to arch structures, because the largest first order moments may not occur at the ends of the arch. Large second order moments may arise in regions where first order moments are small, but deflections are large. Dr. Christian Menn proposed a method of moment magnification for arches that directly computes second order moments from first order deflections and the normal force in the arch[4]. This procedure provides a more realistic estimate of second order moments throughout the length of the arch rib, and was chosen by the design team to address slenderness effects for the Fulton Road bridge design.

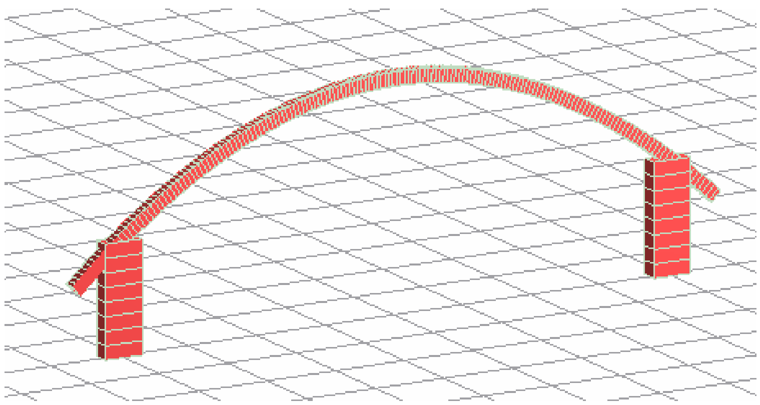

Fig. 19 The extended arch used to derive the k-factor for the new Fulton Road Bridge shown superimposed on the piers of the actual structure

For arches fully fixed at the spring line, the moment magnification procedures of both AASHTO and Menn specify a k-factor of 0.7. While AASHTO provides alternate k-factors for pinned arches, no guidance is given for arches that are attached at the spring line to flexible piers. The piers of the new Fulton Road Bridge provide flexibility to the base of the arch ribs, which makes the fixed arch k-factor of 0.7 non-conservative. The design team has derived a k-factor specifically for the Fulton Road Bridge to account for the presence of flexible piers. The procedure used to find an appropriate k-factor is similar to that developed by early twentieth century bridge engineers who were faced with analyzing multiple-span fixed concrete arches on flexible piers without the aid of computer modeling software. Conde McCullough, famous for the many arch bridges he designed along Oregon's Pacific coast during the 1920s and 1930s, proposed a method of finding a single span extended arch that is equivalent to an interior span of a multiple-span fixed concrete arch bridge on flexible piers[1]. This method is mathematically exact and is prefaced in McCullough's book *Elastic Arch Bridges* by the humbling statement that it allows "an experienced designer [to perform the structural analysis by hand]…in a period not to exceed forty-eight hours"[1].

In a similar fashion, the design team has developed an approximate extended arch procedure to derive the k-factor for the new Fulton Road Bridge. The exact method of McCullough produces an extended arch with sharp discontinuities that would make deriving a k-factor difficult. The approximate method begins by placing an unsymmetrical loading on a freestanding single arch span with the same dimensions as the arches of the actual structure, and resting on the tallest piers that support the arch spans. The piers of the actual structure are founded on shale and are modeled with appropriate foundation springs. An unsymmetrical loading is used to generate substantial arch deflections in the horizontal x-direction. The same loading is next applied to a single arch span with the same profile as the new Fulton Road Bridge, but which is attached at the spring line to a fixed support instead of flexible piers. This fixed arch is then extended in length following the same parabolic equation as the profile of the actual structure, until all deflections due to the loading are equal to or exceed the deflections of the actual arch on flexible piers. A k-factor of 0.7 can be used for the extended arch because it is fully fixed at the spring line. The k-factor for the actual structure is found from the equation

$$(k_{actual})(length_{actual}) = (0.7)(length_{extended}) \quad (1)$$

where $length_{actual}$ is the arc length of the actual structure between its pier spring line and crown, and $length_{extended}$ is the arc length of the extended structure between its fully fixed spring line and crown.

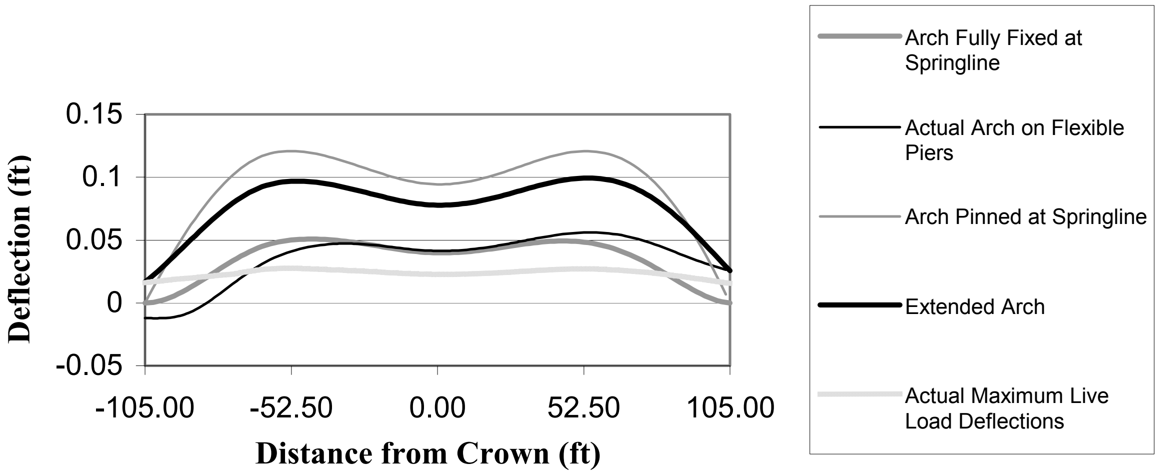


Fig. 20 Plot showing unbalanced vertical spandrel load deflections of the actual structure, extended arch, and arches pinned and fixed at the spring line of the actual structure.

A plot of the horizontal x-direction deflections of the actual arch, the extended arch, and arches pinned and fully fixed at the spring line location of the actual arch is shown in Fig. 20. From inspection of the plot, deflections in the horizontal x-direction are approximately equal for both the actual and extended arches at the spring line location of the actual structure. Horizontal deflections, vertical deflections, and in-plane rotations are otherwise much larger for the extended arch than the actual structure. These results give confidence that the k-factor found for the actual structure using the extended arch technique will yield conservative results for second order moment analysis. For further verification, the results of the second order analysis using this k-factor are then compared against a computer p-δ analysis of the actual structure for transient loads.

## CONSTRUCTION METHODS

The unique site conditions of the project present additional complications to final design of the arches. For the new Fulton Road Bridge, the presence of two sets of railroad tracks, the historic Brookside Park Bridge, and the Cleveland Metroparks Zoo under the arch spans make the use of extensive falsework to cast the arch ribs in place or temporary towers to support precast arch segments impractical. The design team has explored several alternate methods that allow the new bridge to be constructed without temporary towers. Currently, a balanced cantilever approach is proposed, for which the end arch rib segments of adjacent spans are hung symmetrically from the end piers by steel bars or cables. The middle segment of each span is placed on strongbacks attached to the end spans. After insertion of the middle segment, closure between segments is made, post-tensioning is completed, and the bars are removed. This construction method places additional structural demands on the pier columns for temporary loads during erection. This incremental cost, however, is considered preferable to the use of temporary towers beneath the structure.

Additional design challenges are associated with the construction method chosen for the new structure. These include:

- Analyzing the structure for each phase of the construction sequence, including the evaluation of time dependant creep, shrinkage, and post-tensioning loss effects that must be accounted for by using realistic construction phase durations.

- Evaluation of stresses in the segments at each construction phase, and providing for strength requirements in the cast-in-place end piers to resist the unbalanced moments during construction.

- Providing sufficient upward camber in the end segments to allow the arches to deflect into the correct geometric location after the addition of the superstructure dead load and the accumulation of creep and shrinkage deflections. The camber during each construction step is significant for force calculations, since the dead load and prestress arch moments of each construction phase are influenced by the corresponding geometric location of the arch rib.

## ANALYSIS TOOLS

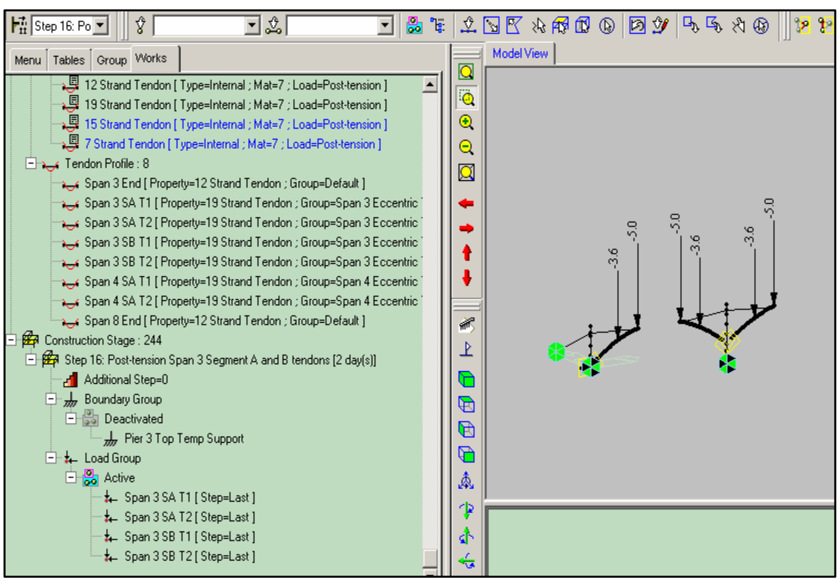


Fig. 21 Screenshot of computer analysis of balanced cantilever construction for the new Fulton Road Bridge.

The design team is using a finite element modeling program that features extensive construction staging and time-dependant creep, shrinkage, and post-tensioning cap-abilities. The user is permitted to control the length of elements without moving end node locations. This feature allows the cable lengths necessary for proper arch rib cambering to be determined without the introduction of cable tensioning forces, or the manual movement of nodes. Output is exported to spreadsheets where moment magnification is applied and stress plots are produced. The moment magnification results are compared to p-δ results from the computer model. Strength design of the arch ribs is performed using column design software, and the finite element model is used to evaluate buckling.

## CONCLUSIONS

The proposed Fulton Road Bridge Replacement is a contemporary precast, post-tensioned, continuous arch bridge that incorporates modern materials and analysis methods to provide a safe and efficient structure that meets the public's demand for a new structure that respects and resembles the existing bridge. The design represents a constructible alternative that preliminary estimates indicate can be built with the funds available, and which satisfies the majority of the concerns of the public and key stakeholders. The solution utilizes precast concrete to minimize impact to a major public facility, the Cleveland Metroparks Zoo, beneath the structure, and to address the need to reconstruct the new bridge in a short time frame. The precast, post-tensioned arch ribs that comprise the new structure will provide for a durable and aesthetically pleasing bridge.

Final design of the chosen alternative is currently underway and will be completed by the end of 2005. The new Fulton Road Bridge is currently scheduled to be open to the public by the end of 2008.

## REFERENCES

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4. Menn, C., *Prestressed Concrete Bridges,* Birkhauser Verlag, 1990.
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