The Influence of Arch Flexibility On The Floor Deck Structural Characteristics For Composite Arch Steel Bridge

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Abstract. This paper presents an optimizing design for the floor deck for the composite arch steel bridge depending on the arch flexibility (the bridge's main component). The design is based on second-order effects using nonlinear p-delta analysis. Many variables are considered in the parametric study, which is the arch's in-plane flexibility, the out-of-plane flexibility of the arch, and the number and stiffness of the lateral bracing between the twin arches. The design has been done by graphical design software SAP2000 and based on AISC and AASHTO specifications. A numerical example is studded herein for the new proposed bridge of Batta in Al-Hilla city in Iraq which crossover Al-Hilla river for a width of 108m from bank to bank, the bridge has an overall width of 18 m including two lane-two way of 15.6 m width and walkways of 1.2 m on both sides. This study's main objectives are the number and size of floor beams, deck thickness, and hence the overall weight of the bridge will be minimum, the goal of design is to select the lightest and most economical and practical composite floor decks. It has been concluded that the deflection decreases with the increase in the number of the floor beam, and the best result was the case of the distance between the floor beam is 1.95 m with a deflection of 71.95 mm, meaning that the flexibility is less as the number of floor beam increases. As for the change of the arch's cross-section, the best result of the lesser girder deflection was in the case that the arch section with dimensions (0.8 x1.2x0.035) m. This indicates that the greater the moment of inertia, which leads to less deflection for cross over the main girder.

Keywords: Steel Arched Bridge, in-plane flexibility, composite concrete deck.

1. Introduction
Arch bridge construction is one of the most common bridging methods, and there is already much research on it from various aspects [1]. In 2011, Miguel Ortega Cornejo and Jorge Nebreda Sánchez examined the Design and Construction of Composite Tubular Arches with Network Suspension System. Francisco Millanes Mato has introduced the latest Nielsen V-hanger system in the field of steel flow arched bridges, with an extremely slick main feature that makes important saving in steel with very slender main elements, owing to the remarkable reduction of bending stresses in the arches and tie beams [2]. In 2013, at this paper, Kangming Chen, Shozo Nakamura, Baochun Chen, Qingxiong Wu and Takafulmi Nishikawa offered a study Comparing Steel arch bridges in China and Japan. By reviewing the status and progress of steel arch bridges, China and Japan as well as an outline of the design vehicle load and design approach toward global buckling for such bridges [3]. In 2014, Kyriakos Stathopoulos, Savvas Vlachos, Pavlos Thanopoulos researched the design of the
Tsakonas Arched Bridge because the National Road Corinthos-Tripoli-Kalamata in Southern Greece was cut by an extended landslide and the need for the construction of a single large structure to bridge the entire landslide in a region of high seismicity emerged [4]. In 2015, Alessio Pipinato investigated the structural analysis and design of a multi-span network arch bridge by presenting a study of a traditional 1.1 km bridge in the north of Italy against a background of new infrastructure growth [5]. In 2018, Ian Anderson researched the Composite Arch Bridge's assessment that a Composite Arch Bridge (CAB) system, known as Bridge-in-BackpackTM was constructed on a low-volume road in a rural setting by the Vermont Agency of Transportation (VTrans). From the early stone arch to the reinforced concrete arch to the steel arch and steel-concrete composite arch bridge [6].

There are many different arch bridges types and arrangements; a deck arch is one where the bridge deck, which includes the structure that supports the traffic loads directly, is located above the arch's crown. The deck arch is also known as an arch that is true or perfect. A through the arch is one where the bridge deck is situated at the arch's spring line. A half-through arch is the bridge deck's position at an elevation between a deck arch and a through arch [7]. The arch bridge's basic concept is its curved design, which does not directly drive download, but instead transmits them the supports on each end along the curve of the arch. The weight of the entire bridge is borne by these supports called (abutments) responsible for keeping the arch in an unmoving position in the exact positions. The weight pushes the surrounding rocks down and outward, making the entire structure very rigid and solid [8]. The deck section type adopted is one of the significant design decisions. Since the most common types adopted are composite and concrete deck solutions, they are briefly compared by considering the large deck's width, approximately 18 m, a concrete deck would be required with a thick slab [9].

2. Main Objectives

This study's main objectives are to study the influence of arch flexibility on the arrangement and size of floor beams, concrete deck thickness, main girder, crossover girder and hence the overall weight of the bridge will be minimum by using graphic design software SAP2000. Also, to investigate the overall behavior of the arched bridge, and comparing the results with the ones obtained using FEModel. Also, a simplified method is presented in this paper to the analysis and design of the bridge superstructure elements.

3. Methodology

The through arch bridge taken for this study is the main span of the proposed bridge in the north of Hilla City (BETEH location). The details of the bridge's site, river cross selection and land elevations for study are taken from Directorate of Roads and Bridges, Babylon as shown in Figure (1).

![Figure 1](image.png)  
**Figure 1.** Steel Arch Bridge proposal over Hilla River at BETEH location.
The design is based on second-order effects using nonlinear p-delta analysis. Many variables are considered in the parametric study, which is the arch's in-plane flexibility, the out-of-plane flexibility of the arch, and the number and stiffness of the lateral bracing between the twin arches. The design has been done by graphical design software SAP2000 and based on AISC and AASHTO specifications.

The span of the bridge considered for the study is 108 m length span. Based on the bridge's width, the bridge has an overall width of 18 m including two lane-two way of 15.6 m width and walkways of 1.2 m on both sides. There many types of steel arch bridge depending on the distribution of steel hangers. Here it is assumed to be equally spaced at 6 m. The main arch section will also be assumed as a built-up square box section, with h/b = 1.0, where h: depth of the cross-section arch, b: width of the cross-section arch.

The arch boundary conditions depend on the construction method, which are either pin-ended or fixed-ended with an intermediate hinge or without hinge arch. The hangers will transmit the loads from the deck to the arches as a pin-ended tension member, as shown in the Figure (2).

![Figure 2. Main parts of arch bridge](image)

3.1. Floor Beams Distribution
The design of deck slab depends on the arrangement and numbers of floor beams. Here, many of floor beams are studied starting from the thick concrete deck (without intermediate floor beams), to the closest distribution of 9-floor beams. The number of floor beams will affect the thickness of the concrete slab, size of floor beams, and the lateral bracing system of the main girder during the construction stage. This relation is very complicated due to the interaction of the behavior of those main elements, as shown in Figure (3).
3.2. **Cross Section of Arch**

For investigating the effect of the in-plane flexibility of the main arch, the cross-section dimensions have been changed. Three cases are considered with the same cross-section area but with the different second moment of area, by changing the length and width while keeping the perimeter constant. The section constant is shown in Table (1).

| Table 1. Second Moment of Area for Arches for Different Cross-Sections |
|-------------------------------------------------------------|
| case | Dimension, (m) | Moment of inertia (m⁴) | Flexure rigidity ratio |
|------|----------------|------------------------|-----------------------|
| A    | 1 × 1 × 0.035  | 0.02099567             | 1                     |
| B    | 1.2 × 0.8 × 0.035 | 0.01456757           | 0.69383667           |
| C    | 0.8 × 1.2 × 0.035 | 0.027423766          | 1.306162929          |

3.3. **Crossover Main Girder**

Cross over the main girder will be affected by the arch flexibility characteristics (arch cross-section, a radius of curvature and boundary conditions). Therefore, these girders will behave like a beam on an elastic foundation.

If the stiffness of the arch and the hangers are high \((K_{al} + K_{hl} \rightarrow \infty)\), then the stabilization points of the transverse main girders are almost constant, meaning that the deflection of the cross main girders is almost equal or approach to zero. When the arch and the hangers are more flexible, the deflection of main girder will be greater. Here \(K_{al}\) is the arch stiffness, \(K_{hl}\) is the hanger stiffness at the location of hanger \((i)\), as shown in Figure (4), and expressed as:
\[ K_{hT} = \frac{EA}{L_i} \]  
\[ K_{ui} = \frac{P_i}{\Delta_i} \]  

Where:
- \( L_i \): is the length of hanger member at location \( i \),
- \( P_i \): unit load at location \( i \),
- \( \Delta_i \): deformation along the hanger direction at the same location, here it is in a vertical direction.

The evolution of this deformation using any structural method such as Castiglione’s second theorem.

\[ \Delta_i = \frac{R}{EA} \int_{-\beta}^{\beta} P(\alpha) \frac{\partial P(\alpha)}{\partial F_i} d\alpha + \frac{R}{EI} \int_{-\beta}^{\beta} M(\alpha) \frac{\partial M(\alpha)}{\partial F_i} d\alpha \]  

Where:
- \( R \): radius of arch
- \( EA \): axial rigidity
- \( EI \): Flexure rigidity
- \( \beta \): subtended angle of arch.

Figure 4. cross section for arch bridge.

The first boundary value problem studied for the beam on an elastic foundation is when it is subjected to a point load at its midspan, as shown in Figure 5. The origin of the coordinate system is assumed to coincide with the point of application of the load. For example, using the superposition method to extract an equation for Arch subjected to a concentrated load at an arbitrary distance \( x_i \) from the left end fixed support, as shown in Figure (5).

Any analytical or numerical method can be used to evaluate the nonlinear equation for the elastic foundation (or support) of the crossover girder. Table (2) shows each spring’s stiffness using the same geometry of the assumed main arch of the Betta Bridge.

For simplifying the analysis, the results are numerically expressed in terms of the best fit curve, and the elastic spring stiffness is distributed over the entire span of the girder as shown in Figure (6).
Figure 5. a) Arch subjected to Concentrated load at hanger (i) b) Idealization of crossover girder on elastic foundation analogy.

Table 2. Variation of Elastic Stiffness of Arch with Distance along Bridge.

| Xi, m | Deflection, mm | Stiffness of Arch, kN/m |
|-------|----------------|-------------------------|
|       | case (a) | case (b) | case (c) | case (a) | case (b) | case (c) |
| 0     | 0.0000   | 0.0000   | 0.0000   | ∞        | ∞        | ∞        |
| 6     | 0.2805   | 0.3656   | 0.1220   | 594.18   | 455.93   | 1366.12  |
| 12    | 1.2194   | 1.3813   | 0.8184   | 136.67   | 120.66   | 203.65   |
| 18    | 2.8474   | 3.0714   | 2.4153   | 58.53    | 54.26    | 69.00    |
| 24    | 5.0837   | 5.2371   | 4.7780   | 32.78    | 31.82    | 34.88    |
| 30    | 7.5799   | 7.5852   | 7.5463   | 21.99    | 21.97    | 22.09    |
| 36    | 9.9818   | 9.8042   | 10.2872  | 16.70    | 17.00    | 16.20    |
| 42    | 11.9627  | 11.6138  | 12.5861  | 13.93    | 14.35    | 13.24    |
| 48    | 13.2641  | 12.7944  | 14.1120  | 12.57    | 13.03    | 11.81    |
| 54    | 13.7184  | 13.2049  | 14.6480  | 12.15    | 12.62    | 11.38    |
| 60    | 13.2641  | 12.7944  | 14.1120  | 12.57    | 13.03    | 11.81    |
| 66    | 11.9627  | 11.6138  | 12.5861  | 13.93    | 14.35    | 13.24    |
| 72    | 9.9818   | 9.8042   | 10.2872  | 16.70    | 17.00    | 16.20    |
| 78    | 7.5799   | 7.5852   | 7.5463   | 21.99    | 21.97    | 22.09    |
| 84    | 5.0837   | 5.2371   | 4.7780   | 32.78    | 31.82    | 34.88    |
| 90    | 2.8474   | 3.0714   | 2.4153   | 58.53    | 54.26    | 69.00    |
| 96    | 1.2194   | 1.3813   | 0.8184   | 136.67   | 120.66   | 203.65   |
| 102   | 0.2805   | 0.3655   | 0.1220   | 594.18   | 456.00   | 1366.12  |
| 108   | 0.0000   | 0.0000   | 0.0000   | ∞        | ∞        | ∞        |
Figure 6. Effect of In-plane Flexure Stiffness on Elastic Support of Crossover Girder.

Using the best-fitting equations curves that show the crossover girder can be analyzed as a supported beam resting on an elastic foundation of constant value $k$, using half range Fourier sine series the deflection can be written as:

For the present paper's case study, the elastic foundation constant can be expressed in terms of the in-plane flexure stiffness $EI$. Figure (7) and Equation (5) show this relationship.

Figure 7. The Elastic Foundation Constant in Terms of the In-Plane Flexure Stiffness $EI$

$$k = 24.6E^2 - 160.51E + 345.32$$ (5)

4. Results

Finite element (F.E.) modeling of bridges is now common in the normal design process of new structures or in the assessment of existing structures. It is conducted on SAP2000 Workbench. The through arch bridge taken for this study is the middle span of BETEH bridge. Deflection and moment
at crown arch are determine by using SAP2000 for arch bridge model in cases different distance between the floor beam (S) as shown in Table (3) Since the arch is symmetrical and the loads are equal, we can take the results to half the arch for ease.

Table 3. Deflection and Bending Moment arch at cases the different distance between the Floor Beam

| case | S (mm) | Thickness (mm) | Moment (kN.m) | Deflection (mm) |
|------|--------|----------------|--------------|-----------------|
| 1    | 1.95   | 175            | 1445.09      | 33.78           |
| 2    | 2.6    | 175            | 2428.33      | 68.96           |
| 3    | 3.12   | 175            | 3172.94      | 163.45          |
| 4    | 3.9    | 175            | 3286.2       | 111.93          |
| 5    | 5.2    | 250            | 3339.89      | 189.12          |
| 6    | 7.8    | 250            | 3781.21      | 190.27          |

In order to determine deflection and moment for arch at case change load position on hanger for each case of the difference in the distance between the floor beam the SAP2000 Program is used here. The input, materials, section properties and loads as shown in Figure (8)

![Figure 8. SAP2000 Program input.](image-url)
Table 4. Forces in cases the different distance between the Floor Beam for half arch

| x (m) | 1   | 2   | 3   | 4   | 5   | 6   |
|-------|-----|-----|-----|-----|-----|-----|
| 6     | 154.29 | 1129.29 | 105.36 | 2539.65 | 122.79 | 3948.8 |
| 12    | 229.16 | -515.9 | 180.24 | -654.5 | 197.67 | -893.15 |
| 18    | -206.24 | -1659.18 | 85.21 | -1798.72 | 213.15 | -1838.26 |
| 24    | 203.42 | -1904.68 | 160.03 | -2292.17 | 280.02 | -2643.6 |
| 30    | -94.8 | 958.2 | 153.66 | -1167.8 | 200.63 | -1204.9 |
| 36    | -67.02 | 521.3 | 78.89 | -627.37 | -125.76 | -733.43 |
| 42    | -122.68 | 740.07 | -111.12 | 866.575 | -220.16 | 993.08 |
| 48    | -91.32 | 1729.91 | -36.25 | 2109.58 | -145.28 | 2489.26 |
| 54    | -5.9 | 2069.59 | 42.33 | 2621.27 | -55.83 | 3172.94 |

Table 5. Deformation in cases the different distance between the Floor Beam for half arch

| x (m) | ① × 10⁻³, rad Δ, mm | ② × 10⁻³, rad Δ, mm | ③ × 10⁻³, rad Δ, mm | ④ × 10⁻³, rad Δ, mm | ⑤ × 10⁻³, rad Δ, mm | ⑥ × 10⁻³, rad Δ, mm |
|-------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| 6     | -0.212 | 1.12 | -0.04 | 1.25 | -0.25 | 2.14 | -2.6 | 3.13 | -2.9 | 4.45 | -2.1 | 6.43 |
| 12    | -0.355 | 1.52 | -0.13 | 1.94 | -0.44 | 2.21 | -3.6 | 4.32 | -3.6 | 5.53 | -3.2 | 7.65 |
| 18    | -0.805 | 2.67 | -0.51 | 3.71 | -1.4 | 6.75 | -0.66 | 7.8 | -0.47 | 8.95 | -0.36 | 9.2 |
| 24    | 0.751 | 9.89 | 0.81 | 10.75 | 0.743 | 12.61 | 2.9 | 14.73 | 3.2 | 17.14 | 2.97 | 18.58 |
| 30    | 2.6    | -8.16 | 2.28 | -8.78 | 34.7 | 6.39 | 5.7 | -10.89 | 6.39 | -12.39 | 9.46 | 21.74 |
| 36    | 3.5    | 27.38 | 2.92 | -32.94 | 4.98 | -36.5 | 6.7 | -45.98 | 6.99 | -53.15 | 6.25 | -68.51 |
| 42    | 3.3    | -49.34 | 2.51 | -57.29 | 4.71 | -67.24 | 5.8 | -80.91 | 6.99 | -93.69 | 5.33 | -113.83 |
| 48    | 1.8    | -65.93 | 1.3 | -78.46 | 2.8 | -90.98 | 3.4 | -106.6 | 3.5 | -123.3 | 3.03 | -146.18 |
| 54    | -0.098 | -71.95 | -0.21 | -85.68 | -0.15 | -99.42 | 0.3 | -116.22 | 0 | -134.29 | 0 | -157.86 |

Figure 9. Deflection of crossover girder for different floor beam arrangements
Deflection and moment for the center of crossover girder by changing dimension of a cross-section of the arch. The results were as shown in Table (6).

Table 6. Deflection and moment for cross over girder by changing dimension of a cross-section of the arch

| x   | (a)1x1x0.035 | (b)1.2x0.8x0.035 | (c)0.8 x1.2x0.035 |
|-----|--------------|------------------|-------------------|
|     | Deflection(mm) | Moment (kN.m)    | Deflection(mm) | Moment (kN.m) | Deflection(mm) | Moment (kN.m) |
| 6   | -2.4         | 1129.29          | -2.42           | 1152          | -2.4           | 1336          |
| 12  | -0.75        | -515.97          | -1.09           | -674          | -1.67          | -885          |
| 18  | 1.47         | -759.18          | 0.22            | -943.87       | -1.48          | -1179         |
| 24  | -2.88        | -1940.68         | -5.48           | -2011         | -8.88          | -2187         |
| 30  | -14.76       | -1431.27         | -17.25          | -2023         | -20.1          | -1436         |
| 36  | -35.75       | -521.3           | -36.03          | -426.55       | -36.13         | -306          |
| 42  | -57.44       | 740.07           | -54.73          | 890           | -51.22         | 1105          |
| 48  | -74.38       | 1729.91          | -69.24          | 1910          | -62.84         | 2202          |
| 54  | -80.99       | 2069.59          | -75.03          | 2250.97       | -67.67         | 2571          |
5. Conclusions
Through the extracted results, the conclusions are drawn:
1- The flexibility of the superstructure of bridge will decrease with the increase in the number of the floor beam.
2- The number of floor beam will influence both the deck slab thickness and the lateral bracing of the main girder.
3- For the case study considered in this study, the best result was when the distance between the floor beams is 1.95 m with maximum deflection of 71.95 mm.
4- If the second moment of area of the main arch in the case study increases from (0.021) to (0.0411) m$^4$ (95.7%), the deflection will decrease from (80.99) to (67.67) mm (16.45%).
5- The in-plane flexibility of the main arch has a great influence on the stresses and deflection of the crossover girder of bridge.
6- As for the change of the arch's cross-section, the best result of the lesser girder deflection was in the case that the arch section with dimensions (0.8 $\times$ 1.2 $\times$ 0.035) m. This indicates that the greater the moment of inertia, which leads to less deflection for cross over the main girder.
7- The floor system of the bridge and hence the crossover girder can be analysed and design as a beam supported by linear elastic spring.
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