Stability Analysis of Tied-Arch Bridges Under IRC Loading Condition Using Finite Element Method

K. S. Yogesh and Anubhav Singh

Abstract Tied-arch bridges are structured so as to guide outward horizontal forces of the arches to the chord tying both arch rib ends and further to the support through deck-connected tie-rods. Finite element is most often used method to analyze real bridges; we have various number of FE software available; Midas is one of its kind used to accurately simulate the real bridge. A very less effort has been done till now to analyze the tied-arch bridges for IRC loading conditions; this paper investigates the stability of 200 m span bridge under IRC loading cases. Efforts are made to find out the influence of straight, inclined, and network hanger arrangements on the structural behavior of bridge and also to justify the results; thickness of deck slab is varied for the above hanger arrangements. Objective of the work was to determine the most optimal arrangement of hangers along the deck slab for a road bridge, consisting of two steel arches using finite element analysis method. Nonlinear static analytical method was used for the analysis by using an FEM software Midas Civil. Validation of software for AASTO LRFD vehicle was done. 3D models of single span 200 m slab tied-arch bridges for different hanger arrangements have been done to determine maximum displacement, bending moment, and reactions. Deck slab was also varied for the different types of hanger arrangements that determine minimum displacement, minimum bending moment, and maximum support reaction to find the best combination of deck slab thickness and hanger arrangement.

Keywords Tied-arch bridges · Hangers · Arch rib · Nonlinear static analytical method · Midas civil

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1 Introduction

Bridge engineering began with the use of stone and wood for structures as early as from the Neolithic age. Thev oldest arch bridge is the Mycenanean Arkadiko Bridge in Greece which still exists which was built about 1300 BCv". The arches constructed for the bridge were half-circularv, but beginning with the flat arches. Design of arches had further improved by Perrronet at the end of the eighteenth century; his designs were structurally strong to accommodate the upcoming railroad loads. Further, the first theoretical design concepts were introduced by Lahire in the early 1770s using pressure line concept [1].

Tied-arch bridges are structured so as to guide outward horizontal forces of the arches to the chord tying both arch rib ends and further to the support through deck-connected tie-rods. Thrusts acting downwards on a tied-arch bridge's deck are translated to the vertical ties between the deck and the arch through tension force. Same as arch bridge, this tension force tends to flatten the arch and thereby to pushing its tips outward into the abutments. However, in a tied-arch or bowstring bridge, these movements are restrained by the strengthened chord, not by the abutments. This chord ties the tips of abutments together. If we take this thrust as a tension force, the mechanism remains same as our ancient bow with string that is being flattened. Therefore, the design is also called a bowstring-arch or bowstring-girder bridge [2]. The elimination of horizontal forces at the abutments allows tied-arch bridges to be constructed with less robust foundations; thus, they can be constructed atop elevated piers or even on unstable soil. Since their construction does not depend on horizontal compression forces for their integrity, tied-arch bridges can be prefabricated offsite and subsequently floated, hauled, or lifted into place [7].

2 Tied-Arch Structural Behavior

Overall structural arch behavior is demonstrated in Fig. 1, a two-hinged arch. The arch is acted upon by intermediate, transverse, downward point loads. Under this loading, the arch deflects, shortening along the longitudinal axis to create axial thrust which is, in turn, resisted by inclined reactions, R1 and R2. Those reactions have the vertical and horizontal components; therefore, to resist the vertical and horizontal components, we require sizeable foundations or abutments, depending on the subsurface foundation material. The final criterion for the arch requires the arch member to be shaped to avoid bending moments in the rib for downward loads, where in tied-arch brides the pin connections shown for the two-hinged arch are also easily envisioned by the supports affixed to the pier. A typical tied-arch bridge and its components are shown in Fig. 2. The uniform load acts on the concrete roadway deck that is ultimately transferred to the arch hangers. The loading places, the hangers in tension, and displaces the arch rib downward. The arch rib is restrained at each end as for the two-hinged arch, produces an axial shortening, and develops a compressive

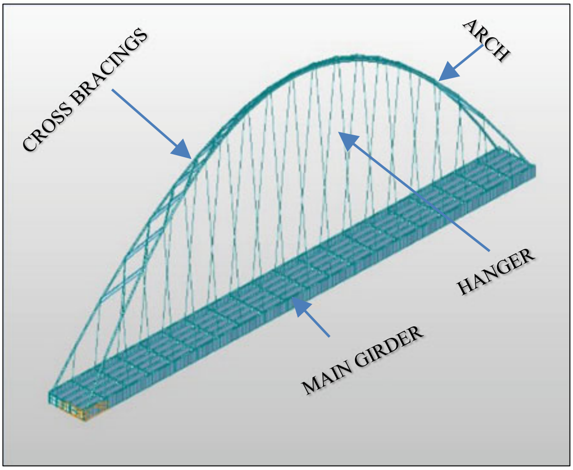

Fig. 1 Typical tied arch bridges showing all its major components

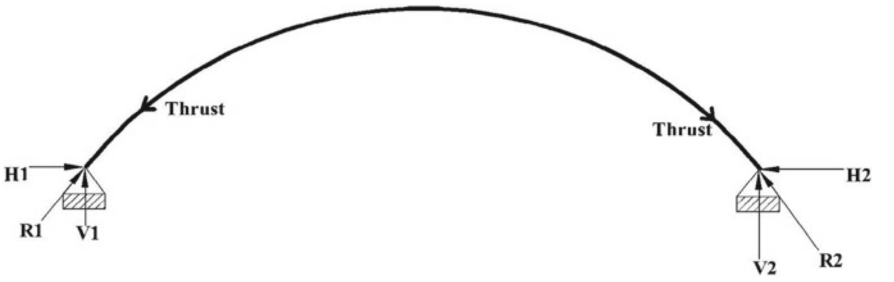

Fig. 2 Typical 2 hinged arch

thrust in the arch rib. Finally, as the arch rib exerts an outward thrust on the supports, the arch tie pulls the supports into equilibrium by loading the ties in tension. From the standpoint of external statics, the single span tied arch behaves in a determinant manner and reacts on the supporting substructure as if it were a simply supported beam [3].

3 Finite Element Analysis of Tied-Arch Bridges

Finite element (FE) is the most suitable method for the static analysis of real bridges [4]. Midas Civil is one of the FE software for designing bridges and civil structures. It has a characteristically user-friendly interface, and the most important is it has an optimal design solution functions. Its highly developed modeling and analysis functions to creating high-quality designs, by overcoming common challenges and inefficiencies of other FE analysis software. As most of the structural components are predefined, user has to just pick the suitable and give the dimensions and other structural specifications. It is also enabled with FE updated procedure, which made able to assign most sensitive variables to the problems and able to solve as gradient-based methods, response surface methods, and nature-inspired algorithm optimization problems [5].

In this analysis, four-nodedv shell elements were used for concrete slabs deck, solid two-node 3D beam elements were used for transverse cross-beams of the deck, bracing members and ties were modeled as beam elements and hangers, respectively, and solid elements were used for arch ribs. Two lateral box stringers are directly assigned from the material library [6].

4 Methodology

This paper signifies to perform stability analysis of tied-arch bridges under IRC loading cases, as very less effort has been taken till now to analyze the tied-arch bridges for IRC loading conditionsv; this investigation is to determine the stability of 200 m span bridge under IRC loading cases and influence of different hanger arrangements. Efforts are also done to find the deflection, bending moment, and reaction for the varying thickness of deck slab for straightv, inclined, and network type of hanger arrangementsv. Objective of the vwork was to determine the most optimal arrangement of hangers along with range of thickness of deck slab for a road bridge. To publish an approachable design methodology to analyzev and design tied-arch bridges under IRC loading conditions.

4.1 Parametric Study: 1

In this study, different types of hanger arrangements like straight, inclined, and network have been modeled and static nonlinear analysis was carried out to identify the variation in deflection, support reactions, and bending moment for the following specification standards and design parameters (Tables 1 and 2).

Table 1 Model specification standards as per T.J.M Smit [6]

1.	For economical design a single span of the tied-arch bridge should be	200 to 300 m only
2.	Height of the arch	1/5 to 1/7 of span
3.	For a bridge of span greater than 255 m, the number of hangers on each side should be	Between 42 and 52
4.	Profile of arch rib	H profile with 10° inclination from vertical

Table 2 Design parameters for modeling

1.	Span of bridge	200 m
2.	Height of arch	40 m
3.	Width of deck	15 m
4.	Dead load	Self-weight of bridge
5.	Live load	IRC loading conditions as per IRC 6 2000
6.	Lane	2 lane—2 way traffic
7.	Density of concrete	25 kN/m^3
8.	Density of wearing coat	22 kN/m^3
9.	Modulus of elasticity	$2.05e + 08$ kN/m^2
10.	Poisson's ratio	0.3
11.	Thermal coefficient	$1.2e - 05$ 1/C
12.	Density of steel	76.98 kN/m^3

Figure 3 shows 3D model of bowstring with x-bracing and straight hangers; distance between two hanger rods is 10 m; H profile with varying thickness and distance between each arch rib is provided. Figs. 4, 5, and 6 show its displacement contours, reaction, and bending moment variation, respectively, of the tied-arch bridge modeled using Midas Civil 2018 (v 2.1).

Similarly inclined and network hanger arrangements were modeled to determine maximum displacement, reaction, and bending moment. Fig. 7 shows inclined or V hanger arrangement, and Fig. 8 shows network or Neilsen arch with x-bracing arrangement.

Table 4 shows comparison of maximum values of reaction, bending moment, and deflection, for above hanger arrangements.

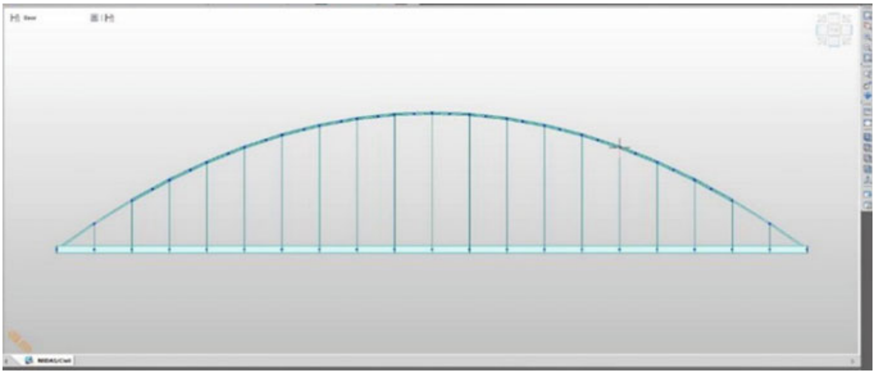

Fig. 3 Bowstring with x- bracing and straight hangers

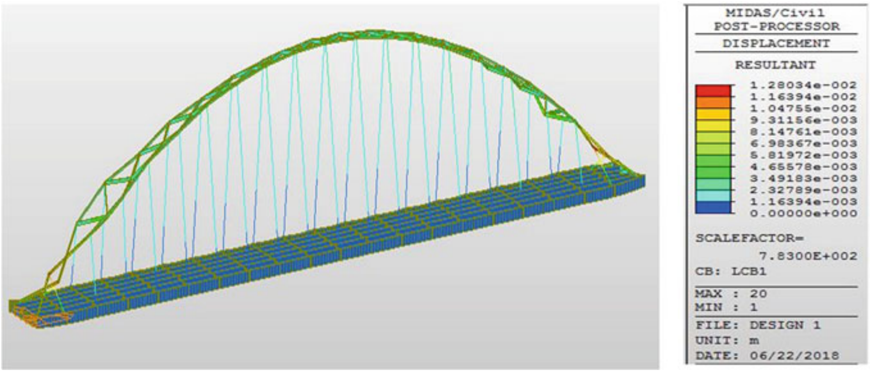

Fig. 4 Displacement contour of bowstring with x-bracing and straight hangers

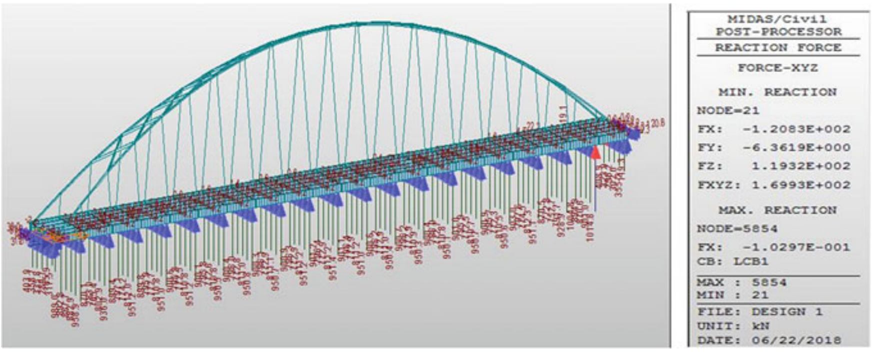

Fig. 5 Reactions of bowstring with x- bracing and straight hangers

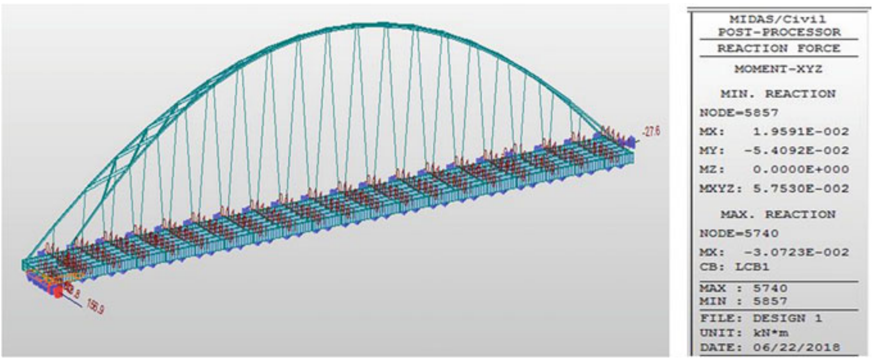

Fig. 6 Bending moment of bowstring with x- bracing and straight hangers

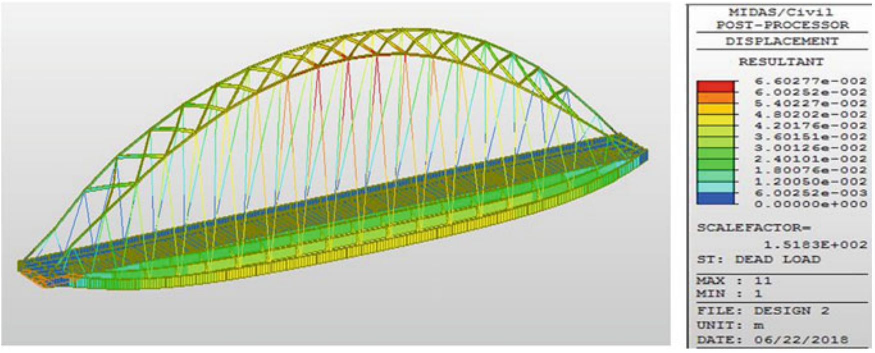

Fig. 7 Displacement contour of x-bracing with inclined or V hanger arrangement

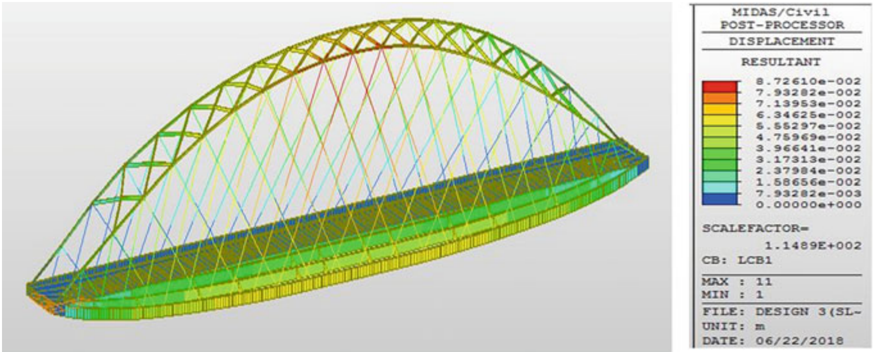

Fig. 8 Displacement contour of x-bracing with network or Neilsen arch

4.2 Parametric Study: 2

Further deck slab thickness is varied as 250, 350, and 450 mm to identify the optimum hanger arrangement with the varying thickness, and the results are given in Table 4.

5 Conclusion

In this paper, static nonlinear analysis of tied-arch bridges is carried out for IRC loading cases using FE methodology using Midas Civil software. The software contains user-friendly interface consuming less time to providing accurate results. As the structural behavior of arch rib is same as two-hinged arch, arch member should be so shaped that there is very less bending moment generated, transfer of reaction should be maximum to the deck support, and maximum deflection should not exceed 1/800 of the span. As per Table 3 for 250 mm-thick slab, we can conclude that network hanger

Table 3 Comparison table

	Straight hanger	Inclined hanger	Network hanger
Maximum support reaction (kN)	5740	5489	5849
Maximum bending moment (kN-m)	151.8	257.8	144.9
Maximum deflection at center (mm)	20	16.6	13.8

Table 4 Comparison table of varying thickness

	Straight hanger			Inclined hanger			Network hanger		
Thickness (mm)	250	350	450	250	350	450	250	350	450
Max. support reaction(kN)	5740	6059	6527	5489	5919	6325	5849	5925	6283
Max. bending moment (kN-m)	151.8	187.5	135.9	257.8	239.4	224.8	144.9	159.6	148.1
Max. deflection at center (mm)	20	17.6	14.3	16.6	13.7	11	13.8	11.2	7.4

arrangement has most optimistic results than straight and inclined arrangements. It transfer around 2% more reactions to the support compared to straight and 6.5% more to the inclined hanger arrangement. Bending moment generated 5% less than straight and 78% less than inclined, similarly straight hanger undergoes 45%, and inclined undergoes 20% more deflection in comparison with network hanger arrangement. Supporting the above statement, Table 4 provides more evidence with the varying thicknesses. Finally, we can conclude that even though straight hanger arrangement transfers comparatively more support reaction and less bending moment to the support but it undergoes more deflection than inclined hanger, whereas the network hanger comparatively transfers maximum reaction minimum bending moment to the support and under goes very less deflection than other two types of arrangements.

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