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Geometrical Considerations of Arch Bridge Design

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ABSTRACT

Arch is nowadays the most popular type of bridges being suitable in mountainous areas as well as in flat terrains. Arches are sometimes above the deck and are called tied arch bowstring. Also, arches may be positioned completely under the deck which is supported on spandrel columns over arch ribs. The configuration of superior deck is particularly suitable for bridging large or deep valleys and canyons, while the bowstring with inferior deck may suit best large water ways of flat valley crossings.

Arch geometry can be either circular, parabolic or inverted catenary and rarely elliptic, all with hinged or fixed end connections. Arch form can also be unusual or irregular geometry such as the Sheikh Zayed Bridge designed by the late Zaha Haddid in Abu Dhabi, U.A.E.

Arch shape should be chosen to ensure that the arch is working predominately in compression, under permanent load. In all cases however, it is worthy to note that the bending moment and shear forces are hardly equal to zero due to permanent loading conditions, although the magnitude of these straining actions will be small even under asymmetric loading cases or support end conditions .

This study investigates the optimum configuration of spandrel arch ribs and tied bowstring arch bridges. For a bridge of given material and a known span, there should exist an optimum geometry. Two steel arch bridges were analyzed and comparison made between the optimum geometric configurations during the in-service condition. The study provides useful data for bridge engineers while designing this type of bridges. An extensive parametric study has been conducted in order to arrive at some reliable conclusions.

Keywords: Tied arch, spandrel arch, hangers/suspenders, funicular/catenary shape.

INTRODUCTION

The construction of modern deck arch bridges started at the beginning of the 20th century using concrete, and the examples are numerous for such bridges spread around the world. This was due to several reasons, firstly by the invention of Portland cement concrete as a high resistance material, in lieu of the masonry stone buildings that have been deployed since the Roman era. As well as for structural considerations where arch by nature is always exposed to compressive forces, and the concrete can resist such stresses efficiently. The spans of these early bridges ranged from 40 to 70 meters and some others reached 160 meters as in case of Cowlitz River Bridge.

The concrete arch was usually designed solid, but the engineers thought of a way to reduce the dead weights, so they emptied the sections to be a hollow box inside. It is noted that this form was commonly used in metallic structures at that time, steel arches emerged then as a strong competitor to concrete, especially with the publication of St. Venant theories in 1843. Today, the free spans of arch bridges reached about 425 meters of the Wanxian Bridge in 1997. This rapid

development is due to the rivalry of steel material to concrete, and the use of composite structures, such as concrete filled steel tube CFST arch bridges.

Erection and construction of arch bridges also developed. Construction methods began with the use of traditional wooden falsework construction and the free cantilever construction then the cantilever construction using temporary stays system to reach the modern hinged rotational construction method. The development in this field is continuing and will not stop as modern new materials will emerge and innovative ways of implementation will enter this field.

The paper discusses the relative stiffness of arch-to-beam based on two steel arch bridges summarized herein and described in details in a previous paper, ref. [1]. It also discusses the behavior of these bridges under asymmetrical load patterns.

BRIDGES' DESCRIPTION

The first of these two bridges is a tied bowstring open timber floor single track railway bridge that consists of two parallel circular arches of span 117 m, whose rise-to-span ratio f/L amounts to 1:6. The attachment of the arch to the tie is secured by a system of axial loaded hangers meeting at panel points. The bridge has a width of 6 m and is provided with two pedestrian lanes of 2.5 m each. The bridge rests on four bearing pads. The hangers of the arch are arranged in a triangular pattern meeting at node points of the arch and the tie beams. The floor consists of 26 cross girders spaced at 4.5 m and 2 stringers running along the whole length of the bridge.

The second bridge is a long roadway viaduct of total length 232 m, whose central arch span is 138 m, the rise-to-span ratio f/L amounts to 1:7. The bridge consists of a pair of parallel circular arches spaced apart 6 m and carries spandrel columns of variable heights. The deck merges over the crown of the arch at a distance of 10 m. Fifteen cross girders spaced apart 6 m., carries the reinforced concrete slab of the deck.

METHOD OF ANALYSIS

The two above described bridges where analyzed and their yielded results were assessed. The bridges were subject to a uniformly distributed loading as in figures 2, 3, 6, 7, 8, 9. Influence lines were also plotted and shown in figures 4 & 5. Egyptian Codes are used in this study ref. [3 & 4].

A 3-D finite element models were used to simulate the actual response of the two bridges. The commercial package SAP was used to perform a linear elastic analysis for the two bridges within the different loading cases. The beam, spandrel columns and braces were analyzed in planar and 3D systems as straight lines connected to two nodes. The arch was subdivided into small straight segment of frame elements. A four-node shell elements were used and abstracted to 2D elements by storing the third dimension as a thickness on physical property table.

The boundary conditions were studied. The hinged support was prevented from displacement in both horizontal and vertical directions. The roller support was only prevented from displacement in the vertical direction. To account from the lateral restrains of the compressed arch, the top compression flange was prevented from lateral displacement.

The stress-strains curves of the structural elements we chosen as follows:

The steel elastic material of the arch, spandrel columns and the main girders is of grade 52, has a Young's modulus E = 210,000 MPa and Poisson's ratio = 0.3. The hangers Dywidag steel bars were used of grade 100, whose yield stress = 5.52 ton/cm^2.

RESULTS DISCUSSION

The present study revealed the following:

The use of rigid strong arch in comparison of the deck beam is preferred over the weak arch-strong beam arrangement. This statement was proved by fig. (2 & 3) and can be applicable to both bowstring and spandrel bridge cases as well.

In tied arch case, the use of vertical hangers can be harmful to both arch and tie beam. In modern design however, vertical hangers are replaced by triangulated system meeting at node points or inclined intersecting hangers to contribute carrying part of the shear forces. The effect of hanger's arrangement on the behavior of the whole system has been clearly demonstrated in a previous publication, Ref. [4], refer to Fig. (1).
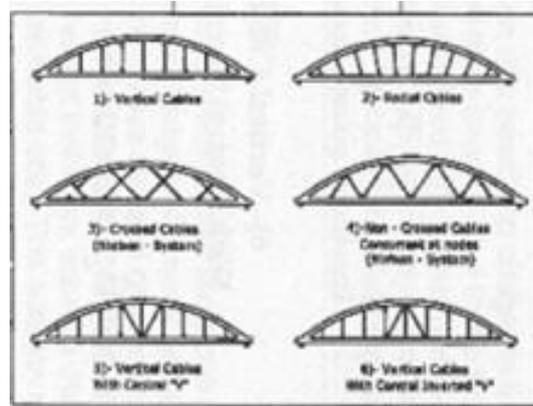

Fig. 1: Different hangers' arrangement for bowstring bridges
[After Abbas reference (1)]

$I(arch)=0.1I \qquad I(tie)=10I$

$I(arch)=10I \qquad I(tie)=0.1I$
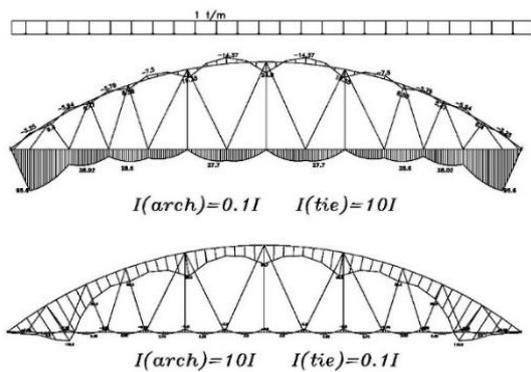
coclusion; we can take $I(arch)=I$, $I(tie)=0.6I$

Fig. 2: Bending moment for a bowstring bridge

B.M.D for strong M.G. case
(Arch= 0.1I & M.G.= 10I)
fully loaded with uniform unit load

B.M.D for strong arch case
(Arch= 10I & M.G.= 0.1I)
fully loaded with uniform unit load
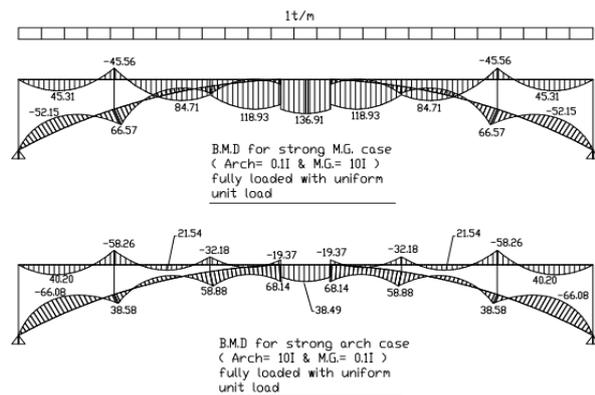
Fig. 3: Bending moment for a deck bridge with spandrel columns

Steel arches are to be preferably designed for flexible deck and near-to-stiff arch rib. However, very stiff arches do not improve significantly the behavior of such structures. In conclusion a balanced ratio arch-to-beam rigidity is recommendable say a ratio of 3:2 or 2:1 could be plausible. Refer to the comparison of figures 2 & 3 which shows that exaggerated high rigidity with respect to the tie or traffic beam is to be avoided.


I Lines For BM at Section A
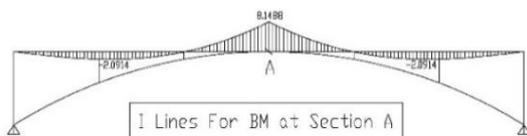
Fig. 4: Influence line for meet point of the bridge

I Lines For Moment at Section H
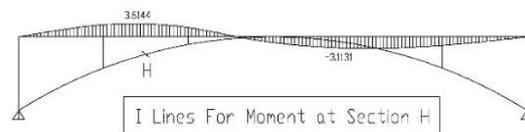
Fig. 5: Influence line for a quarter point on the arch

...eck s...
is characterized by low ratio (q/g). Thus the loading
service load cases are not critical in roadway bridges, although not negligible. Arches are

vulnerable to asymmetric loading cases, while sufficiently strong in resisting symmetrical loading patterns.

Steel arches are subject in most cases to loading reversal, therefore there should be designed for fatigue, refer to figures 4 & 5.
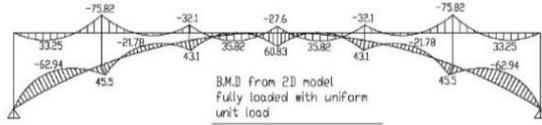

Fig. 6: a 2-D analysis for a fully loaded bridge
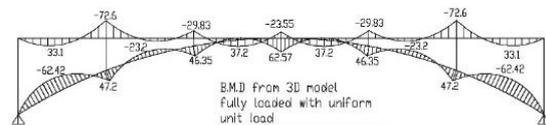
Fig. 7: a 3-D analysis for a fully loaded bridge

Figure 6 shows the bending moment distribution acting on the deck bridge elements for 2-D analysis. While figure 7 shows the same for a 3-D analysis. Figure 8 shows the bending moment distribution of a bowstring bridge for a 2-D analysis and figure 9 for a 3-D analysis.

From these four figures it can be concluded that for the railway bowstring structure, a 2-D analysis is quite acceptable due to the symmetry of loads. While for the roadway bridge a 3-D analysis will yield more accurate results. Same results were previously obtained ref. [5].s
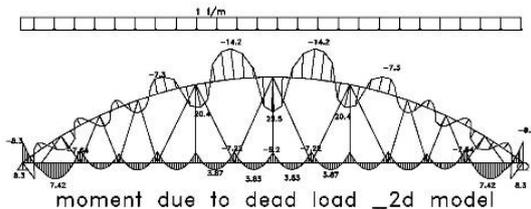

Fig. 8: a 2-D analysis for a fully loaded bowstring bridge
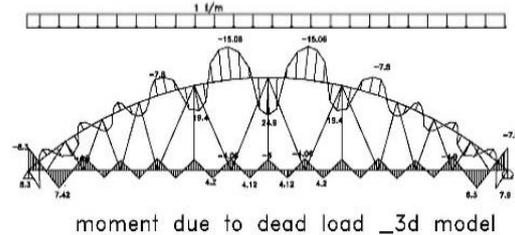
Fig. 9: a 3-D analysis for a fully loaded bowstring bridge

Acknowledgment

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