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A MODERN APPROACH TO TIED-ARCH BRIDGE ANALYSIS AND DESIGN

BY

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Abstract. One of the main feature of the arch bridge is the transmission of external forces to arch ends. When arches are situated under the deck, these external forces are transmitted directly to the land, imposing land with high load capacity and high costs of foundations. In order to reduce foundation costs, tied-arch bridges use the deck to take the role as the tension member taking the forces generated in the ends which make this solution more suitable for openings between 70-200 meters distance range where other type of bridges require large sections or other support systems such as stay cables. The general layout of the hangers have been greatly improved with the development of modern computing technology. The purpose of this paper is to investigate the influence of different hanger arrangements using three-dimensional finite element models and the objective was to determine the most suitable solution for a road bridge, with a span of 100 meters, consisting of two inclined steel arches, located on a road with two traffic lanes, subjected to medium traffic.

Key words: tied-arch bridge; hangers; efforts; tension.

1. Introduction

This paper aims to identify the influence of different hanger arrangements for a tied arch bridge with respect to all the variables such as: efforts in arches, ties and hangers.

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The tied arch bridges appear in different hanger layouts. The general layout of the hangers have been greatly improved with the development of modern computing technology. Understanding of the behavior of structures with large number of static indeterminacy was conditioned by the development of computers.

Depending on the inclination of hangers for tied arch bridges, in the analysis we considered three different arrangements, as follows:

a) *Langer system* as in Fig. 1 which requires a deck with high rigidity, who plays the role of a tie for the flexible arches. The deck is suspended by vertical hangers.

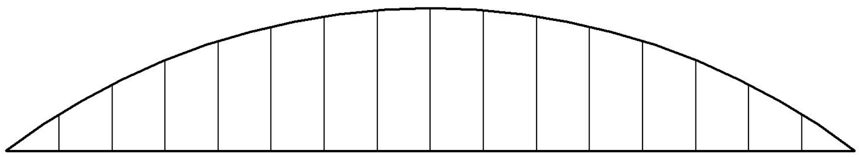

Fig. 1 – Tied arch bridge with Langer configuration of hangers.

b) *Nielsen system* as in Fig. 2 which consists of a single rigid beam, reinforced with a system of hangers. In this system, the hangers are inclined and work as a variable-section truss with rigid bottom “flange”. Nielsen system, patented by Danish engineer Octavius F. Nielsen in 1926, was used in the construction of over 60 bridges at that time.

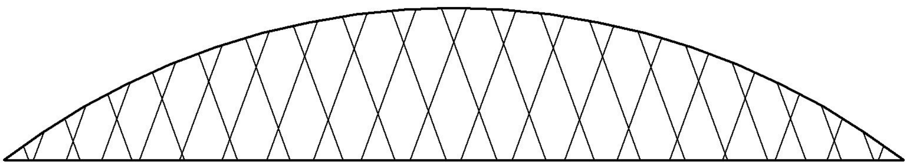

Fig. 2 – Tied arch bridge with Nielsen configuration of hangers.

c) *The network of inclined hangers* as in Fig. 3 as an improved version of the Nielsen system, with the exception that in this case the hangers cross each other at least once. This arrangement of the hangers determine very slender structures and thus reduced material consumption. Inclined hanger network system was patented by Professor Per Tveit from Norway in the 1950s, from the study of the distribution of bending moment bridges Nielsen system.

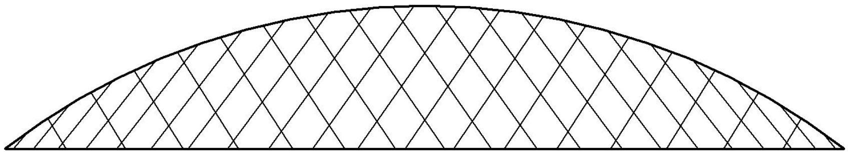

Fig. 3 – Tied arch bridge with network configuration of hangers.

Defining parameters to identify the most effective hanger arrangement requires a complex process that involves several variables such as cost, aesthetics, efficiency and some of the local constraints imposed by landscape. Regarding hangers, the demanding criterion is to reduce the number of the compressed hangers and to reduce the maximum axial force in them.

2. First Order Structural Analysis

An analysis was made for a road bridge with 100 meters span consisting of two circular hollow steel arches with a radius of 82 meters and a maximum height of 17 meters, connected at ends by circular hollow section tie-beams. The arches are inclined inward 15 degrees after the tie-beam axis. Arches are connected at the bottom by means of variable height double T section crossbeams positioned at equal distance of 5 meters and at the top are connected by means of circular hollow sections bracings. A reinforced concrete top slab linked by elastic connectors to the crossbeams completes the composite deck.

Hangers were modeled as rigid bar type elements to evaluate the first order efforts. For this study we considered two types of hangers: the rigid tension rod, and Parallel Wire Strand elastic type hanger. Both links at the top with arches, and bottom with tie beams are pined through fork connectors. Each rod is applied an initial unit pretension force. Conditioned by vertical movement of the deck, the tension must be adjusted properly afterwards.

2.1. Vertical Hanger System (Langer System)

In this configuration the compression forces in the arch increases with the number of hangers as shown in Fig. 5. It was observed that with increasing number of hangers, compression increases in the arches, while the hanger's axial efforts decrease as in Fig. 4.

Bending moment decreases with the increasing number of hangers, and this difference is remarkable when the number of hangers is lower and the bending moments in the arch grow rapidly as shown in Fig. 6.

The tie beam axial efforts variations do not appear in the system with vertical hangers, but the hanger number variation significantly influences the bending moment in the beam because the hangers play the role of elastic supports for tie beam as in Fig. 7.

In this configuration the bending moment dictate the arch sections and the best results for the 100 meters span studied was found for the 20 hanger configuration.

As a consequence, in the arch with vertical hangers, bending is a decisive factor when it comes to the choice of the cross-section of the chords.

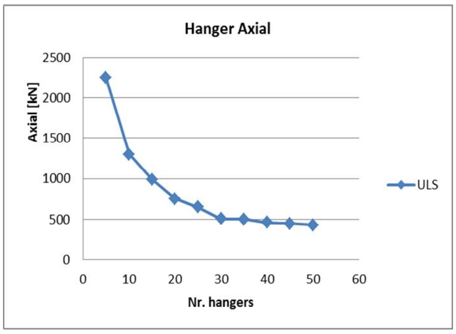

Fig. 4 – Variation of axial force in hangers in vertical system depending on the hanger number.

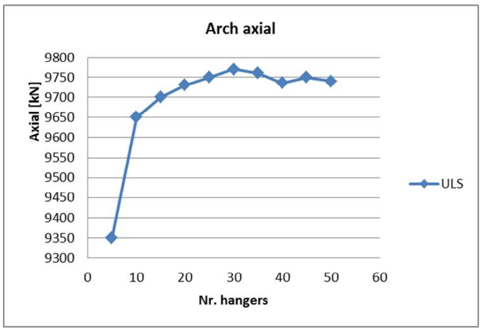

Fig. **Error! No text of specified style in document.**5 – Variation of axial force in arch in vertical system depending on the hanger number.

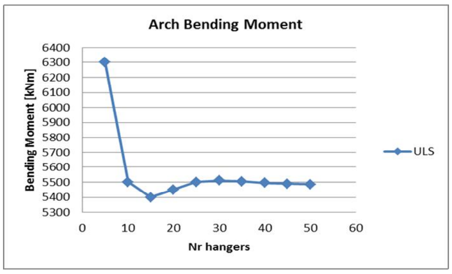

Fig. 6 – Bending moment variation in arch in vertical system depending on the hanger number.

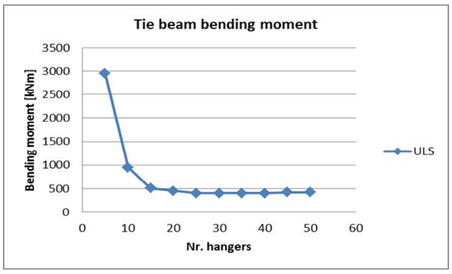

Fig. 7 – Bending moment variation in tie beam in vertical system depending on the hanger number.

2.2. Inclined Hanger System with Constant Slope (Nielsen System)

To simplify the manufacturing process and for a uniform distribution of the moment, and to reduce the buckling length in many cases the hangers are disposed at equal distances along the arc. In this case, the unknowns are the locations of nodes on the tie beam. An alternative is to arrange the hangers at equal distances along the tie beam and the arc node locations are the unknowns.

In this system, the hangers are disposed at equal distances along the arches. Angle with the horizontal plane was set 40 degrees.

As shown in Fig. 9, relaxed hangers number is relatively high in this arrangement. As with the horizontal angle is greater, the higher the number of the relaxed hangers. In each case analyzed the hangers at the ends were always relaxed.

In Fig. 12 we can see that arch compression tends to decrease with the increasing angle to the horizontal plane. This is explained by the fact that more inclined hangers are less tensioned, due to the small horizontal component of the force. The range most effective for this opening is between 60 to 80 degrees. Bending moments in arches shown in Fig. 10. indicate that the suspensions above 75 degrees inclinations involves large bending moments in arches.

In Fig. 13 we can see that tie beam axial force tend to increase with the increasing angle while bending moment shown in Fig. 11 is influenced only by the angles over 70 degrees .

As a conclusion to this configuration, the lighter the bridge, more inclined hangers are necessary and more hangers are relaxed. Still, this configuration determine sections that lead to about 40% smaller material consumption than in the vertical arrangement of hangers.

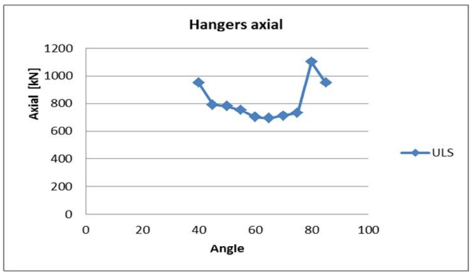

Fig. 8 – Variation of axial force in hangers in NIELSEN system depending on the angle.

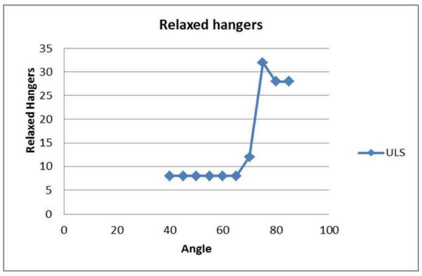

Fig. 9 – Number of relaxed hangers in NIELSEN system depending on the angle.

Fig. 10 – Bending moment variation in arch in NIELSEN system depending on the angle.

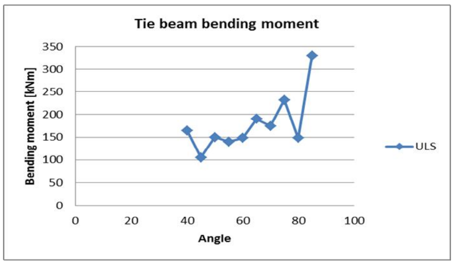

Fig. 11 – Bending moment variation in tie beam in NIELSEN system depending on the angle.

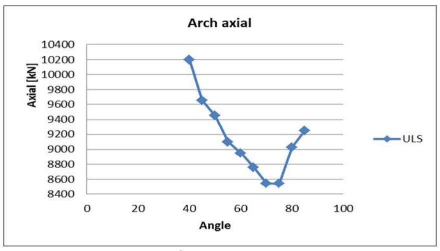

Fig. 12 – Axial force variation in arch in NIELSEN system depending on the

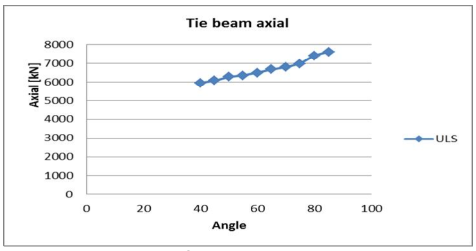

Fig. 13 – Axial force variation in tie beam in NIELSEN system depending on the

angle. angle.

2.3. Inclined Hanger System with Variable Slope (Nielsen System)

Unlike Nielsen system, in this system inclined hangers cross each other at least twice. In general this type of arrangement leads to lower consumption of materials and slender structures. In Langer system the asymmetric load produce considerable deformations in both arches and tie beams, while using the inclined system with variable slope can see deformations only on the tie beam which means a better distribution of efforts in the arch.

Favorable behavior of this system is due to the rigidity of the network of hangers and often transverse bending moments are greater than the longitudinal.

This method follows the same concept as the previous system. Unlike constant inclination system, in this system the slope of each rod is variable by a linear function.

An optimization of the "wheel spokes" is documented and Schanack Brunn, who concluded that if every hanger decomposes in two hangers and the resultant hanger forces pairs is orientated toward the center of the circle of which the arc as shown by below. In this case, the only variable involved is the angle between adjacent hangers at their intersection.

In this system, each set of hangers starting at angle start and then increase or decrease along the bridge. In this study it was considered a first angle of 55 degrees and a variation of 0.5 degrees/hanger.

Fig. 18 shows that maximum axial force in the arch tends to be smaller as the inclination is greater. Bending moment results from the analysis show that the more inclined hangers, the smaller the bending moment as in Fig. 16.

The hanger angle variation does not appear to significantly influence the tie beam axial force Fig. 19. Bending moments along the beam decreases with increasing angle Fig. 17.

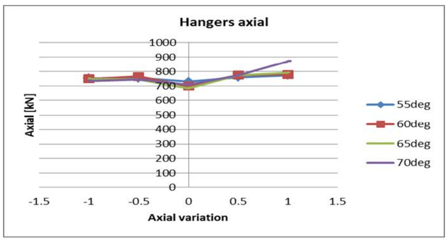

Fig. 14 – Axial force variation in hangers in inclined hanger system with variable slope depending on the angle variation.

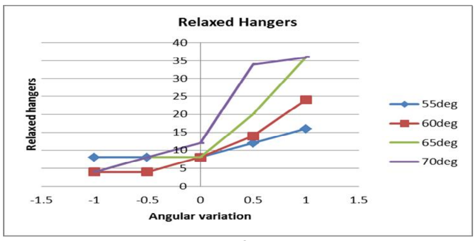

Fig. 15 – Number of relaxed hangers in inclined hanger system with variable slope depending on the angle variation.

Unlike hanger system with constant inclination , for this span were obtained unfavorable results, which in turn lead to larger sections, namely higher costs. However, comparing to a system with vertical hangers, in this configuration we get a 30% lighter structure and relaxation of the hangers remains the problem.

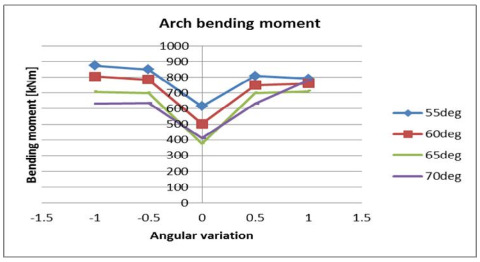

Fig. 16 – Bending moment variation in arch in inclined hanger system with variable slope depending on the angle variation.

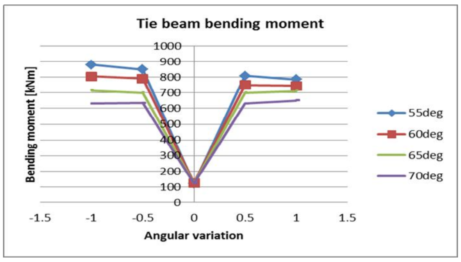

Fig. 17 – Bending moment variation in tie beam in inclined hanger system with variable slope depending on the angle variation.

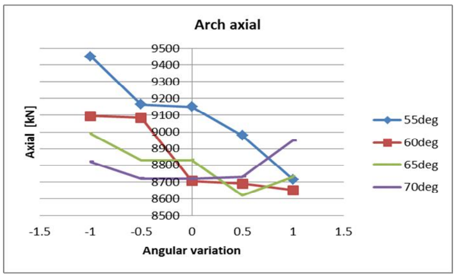

Fig. 18 – Axial force variation in arch in inclined hanger system with variable slope depending on the angle variation.

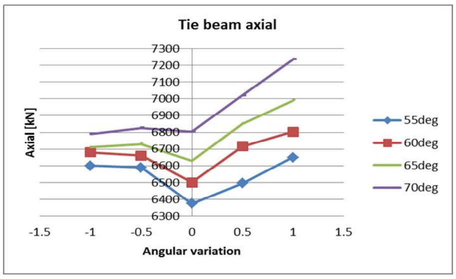

Fig. 19 – Axial force variation in tie beam in inclined hanger system with variable slope depending on the angle variation.

3. Conclusions

In this study, for the opening of 100 m, it can be seen more effective the network system with inclined hangers than the vertical hanger system. This system provides a better structural efficiency compared to the configuration with vertical hangers as seen in Fig. 20.

Regarding other systems examined, it is observed that the system with hangers at an angle determined competitors satisfactory results. The best solution is the one with constant inclination inclined hangers.

It is the stiffness of the hanger web that leads to such small bending moments in the lower chord of the network arch, indeed about ten times smaller in comparison with the conventional arch bridge.

As a result, longitudinal bending does not govern the network arch design. As shown later, this leads to a more efficient use of material, to lower steel weight and to more slender arch cross-sections. Transversal bending moments are usually greater than longitudinal bending moments, causing transversal loads to determine the design of the concrete or of the composite steel-concrete tie.

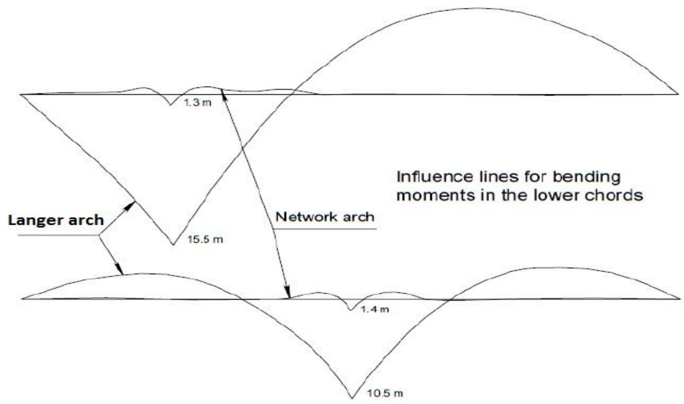

Fig. 20 – Influence lines for bending moments in the lower chords.

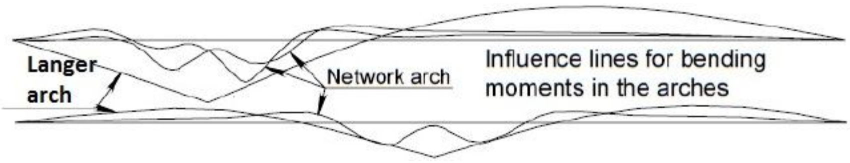

Fig. 21 – Influence lines for bending moments in the arches.

The lowest tension is obtained in vertical hanger configuration. However, this configuration shows large arch bending and tie beams moments.

System with inclined hangers with variable inclination is less effective than the system with constant inclination inclined hangers. Bending moments are almost double in both arches and tie beams compared with the constant inclination of the hangers, and the relaxed hangers are found in larger numbers in this system. In general, the relaxed hangers have greater inclination.

Maximum tension of hangers not only affects the ultimate limit state, but play a role in resistance to fatigue, so have made a thorough study of the fatigue strength of the hangers.

Buckling length of arch varies depending on the number and position of the hangers. A comprehensive analysis of the phenomenon should be performed to optimize structural buckling of the bridge.

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ABORDĂRI MODERNE ÎN ANALIZA ŞI PROIECTAREA PODURILOR ÎN ARC CU TIRANȚI

(Rezumat)

Unul dintre principalele caracteristici ale podurilor în arc este că arcele transmit eforurile exterioare spre nasterile arcelor. În cazul podurilor în arc cu calea sus, forțele exetrioare sunt transmise prin arce direct pamântului de fundare, fiind astfel necesare terenuri de fundare cu capacitante portantă ridicată sau soluții costisitoare de fundare. În cazul podurilor în arc cu tirant, pentru a reduce costurile fundațiilor, tablierul joacă şi rolul de tirant, preluând forțele orizontale din nasterile arcelor, astfel această

soluție devenind una potrivită pentru deschideri cuprinse între 70 şi 200 metri, unde alte tipuri de poduri ar necesita secțiuni mari sau alt tip de susțineri cum ar fi hobanele. Modul de dispunere a tensorilor a evoluat împreună cu dezvoltarea tehnologiei de calcul. Scopul acestei lucrări este să investigheze influența diferitelor moduri de dispunere a tensorilor utilizând modele tridimensionale şi are ca obiectiv determinarea soluției optime de dispunere a tensorilor pentru cazul unui pod rutier cu o deschidere de 100 metrii, alcătuit din două arce metalice înclinate, amplasat pe un drum cu două benzi de circulației supuse unui trafic mediu.