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FEATURES OF DESIGN OF TIED-ARCH BRIDGES WITH FLEXIBLE INCLINED SUSPENSION HANGERS

Purpose. Investigation and analysis of the hanger arrangement and the structural stability of a Network arch bridge – a tied-arch bridge with inclined hangers that cross each other at least twice. It is also necessary to make a comparative analysis with other types of hanger arrangements. **Methodology**. The authors in their research investigated a large number of parameters to determine their influence in the force distribution in the arch. Eventually they determined optimal values for all parameters. These optimal values allowed developing a design guide that leads to optimal arch design. When solving this problem, the authors used 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. The virtual prototype of the model is performed by finite element simulator Midas Civil. **Findings**. In this study, for the bridge deck, a concrete tie appears to be the best solution considering the structural behavior of network arches, but economic advantages caused by easier erection may lead to steel or a composite bridge deck as better alternatives. Design requirements and local conditions of each particular bridge project will decide the most economic deck design. **Originality.** To ensure passenger comfort and the stability and continuity of the track, deformations of bridges are constricted. A network arch is a stiff structure with small deflections and therefore suitable to comply with such demands even for high speed railway traffic. A network arch bridge with a concrete tie usually saves more than half the steel required for tied arches with vertical hangers and concrete ties. **Practical value**. Following the study design advice given in this article leads to savings of about 60 % of structural steel compared with conventional tied arch bridges with vertical hangers.

Key words: tied-arch bridge; vertical hangers; inclined hangers; arch; theories of hangers system; number of hangers; angle of hungers

Introduction

This paper discusses aspects of designing of «network arch» type tied-arch bridge superstructures with the polygonal top chord and flexible inclined hangers. The P. Tveit and B. Brunn – F. Schanack theories are explained. In addition, the authors present results of their own research on synthesis and classification of foreign practices and recommendations as to design of such systems.

Current trends in the engineering of artificial structures are largely driven by the increasingly stringent requirements for their reliability, carrying capacity, durability, cost effectiveness and aesthetic qualities [3, 5]. Concurrently, designed structures must be sufficiently adaptable to streamlined practical implementation at construction, operation and necessary maintenance. The above listed requirements condition need for the use and development of new innovative solutions both at design and construction of artificial structures. The first arch bridge with multiple crossing hangers was designed by Per Tveit and was built in 1963 in Steinkjer in Norway spanning 80 m, see Figure 1 [10, 11].

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Fig. 1. Network arch at Steinkjer (first)
and Bolstadstraumen (second)

In that same year, another two network arches were constructed. The Bolstadstraumen bridge spanning 84 m was also designed by Per Tveit and built in Norway (Fig. 1). Also the Fehmarnsund bridge in Germany spanning 248 m (Fig. 2). The Fehmarnsund bridge is clearly a class bigger than the two Norwegian bridges, not only in span, but also in load carrying capacity. This bridge accommodates two road lanes and a single railway track.

Fig. 2. Fehmarnsund bridge

Purpose

A network arch bridge is a tied arch bridge with inclined hangers intersecting at least twice [3, 5, 10]. Compared with regular tied arch bridges, i.e. those with vertical hangers, the network arch bridge exhibits low moments in both of the chords, which typically leads to important material savings. In Figure 3 it can be seen that the network arch tends to behave like a simple beam, due to its higher stiffness, leading to small deflections. As Figures show, partial loading on half of the span will lead to deflections on the upper and lower chord in the arch with vertical hangers while the arch with inclined hangers only observes deflections on the lower chord.

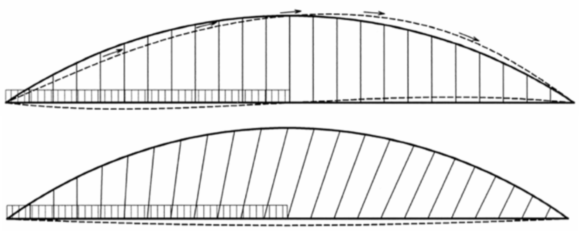

Fig. 3. Tied arch with one set of inclined hangers
submitted to partial loading

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. In the network arch, bending will only occur due to local loading, and therefore the arch and the tie are only subjected to axial forces.

At the practical engineering of such type structures, engineer faces the necessity of solution of the following problems:

– Definition of optimum design parameters of the arch, in particular, outline shape, rise height, construction;

– Choice of hanger net construction scheme;

– Determination of reasonable hanger inclination angle;

– Calculation of the most rational number of hangers;

– Analysis of solution cost-effectiveness as compared to superstructures with vertical hangers;

This paper presents selection of information both from foreign practice of this type bridge designing and construction, and from the author's own researches. It outlines and formulates general principles of designing the superstructures with the inclined hangers and provides general recommen-

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dations for the practical designing of such superstructures.

Methodology

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. The virtual prototype of the model is performed by finite element simulator, Midas Civil.

Findings

Vertical Hanger System (Langer System)

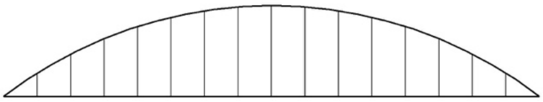

Fig. 4. Tied arch bridge with Langer configuration of hangers

In this configuration the compression forces in the arch increases with the number of hangers as shown in Figure 6. It was observed that with increasing number of hangers, compression increases in the arches, while the hanger's axial efforts decrease as in Figure 5.

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 Figure 7.

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 Figure 8.

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.

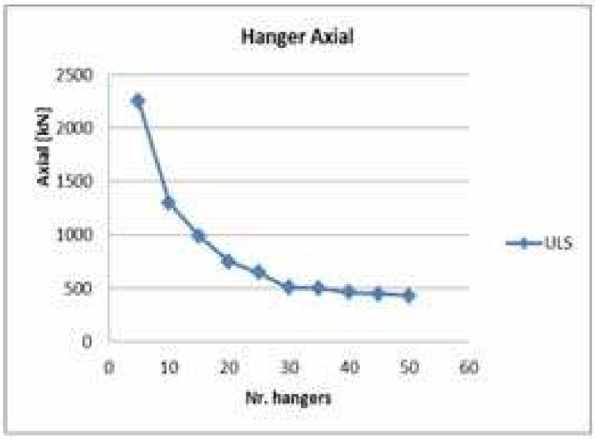

Fig. 5. Variation of axial force in hangers in vertical system depending on the hanger number

Fig. 6. Variation of axial force in arch in vertical system depending on the hanger number

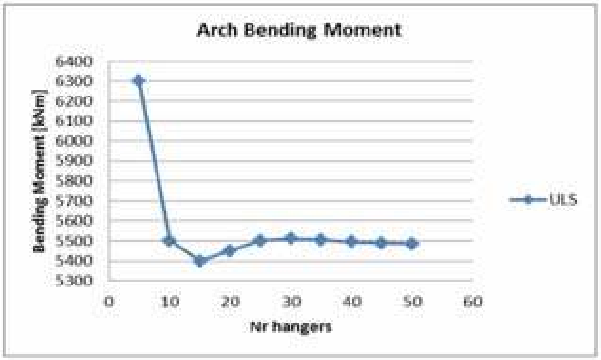

Fig. 7. Bending moment variation in arch in vertical system depending on the hanger number

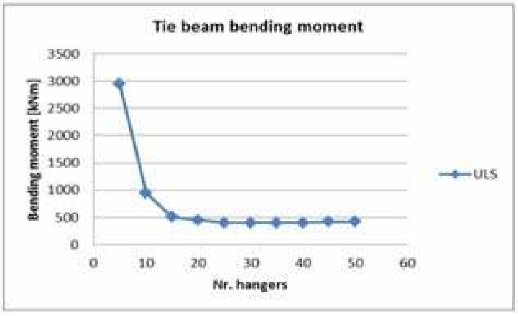

Fig. 8. Bending moment variation in tie beam in vertical system depending on the hanger number

Inclined Hanger System with Constant Slope (P. Tveit theory, Nielsen System)

P. Tveit theory, this method follows the same concept as the previous one [9, 10]. In this case, however, the slope of each hanger varies following, for instance, a linear function like Δφ= α.x+β, where x is the number of the hanger, α and β are the parameters that make the hanger arrangement vary along the length of the arch [4, 5, 10]. A general case is illustrated in Figure 9 Assigning a constant slope is a particular case of this configuration, when α is taken as 0.

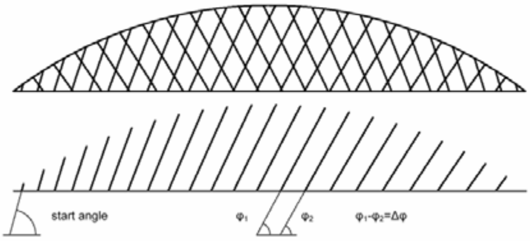

Fig. 9. Tveit net construction scheme

The construction of reverse hangers is carried in inversed manner. Thus the hanger inclination angle variation is considered positive from the right to the left; in the shown scheme, hanger inclination angle becomes steeper from the left to the right [7].

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 [8]. 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 Figure 11, 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 Figure 14 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 Figure 12. Indicate that the suspensions above 75 degrees inclinations involve large bending moments in arches.

In Figure 15 we can see that tie beam axial force tend to increase with the increasing angle while bending moment shown in Figure 13 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 determines sections that lead to about 40% smaller material consumption than in the vertical arrangement of hangers.

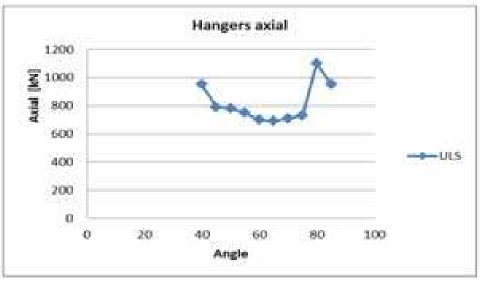

Fig. 10. Variation of axial force in hangers in NIELSEN system depending on the angle

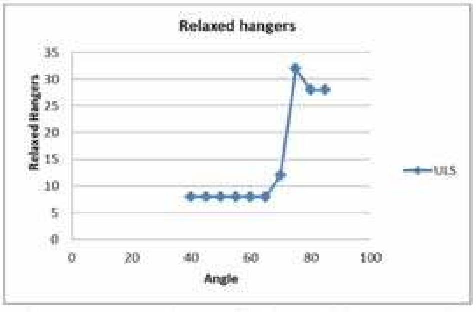

Fig. 11. Number of relaxed hangers in NIELSEN system depending on the angle

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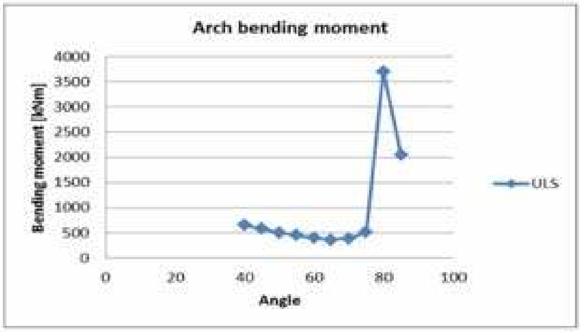

Fig. 12. Bending moment variation in arch in NIELSEN system depending on the angle

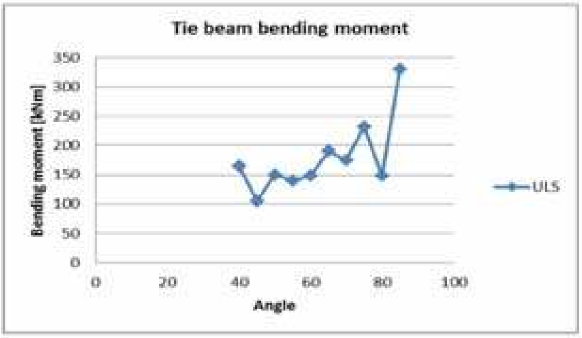

Fig. 13. Bending moment variation in tie beam in NIELSEN system depending on the angle

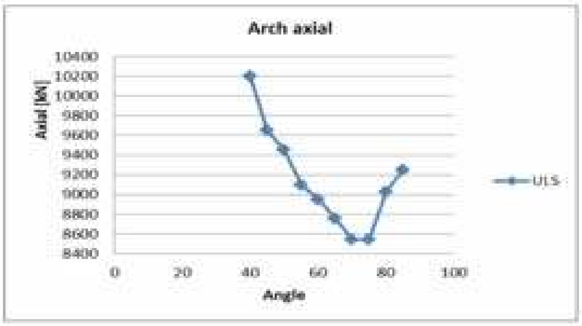

Fig. 14. Axial force variation in arch in NIELSEN system depending on the angle

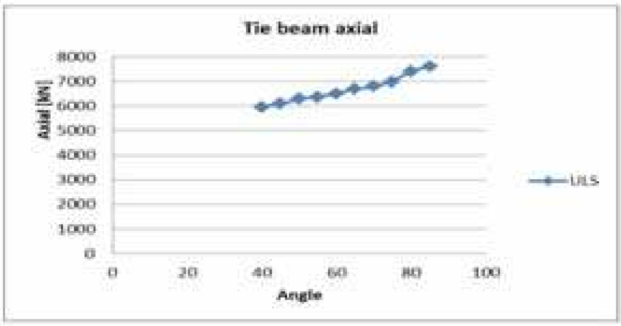

Fig. 15. Axial force variation in tie beam in NIELSEN system depending on the angle

Inclined Hanger System with Variable Slope (B. Brunn and F. Schanack theory, Nielsen System)

B. Brunn and F. Schanack theory is based on the arch thrust line and implies the constant value of hanger inclination angle [1, 2, 5]. This model shows that if the forces in each hanger were approximately equal, the «resulting force» would lie on the radii of the arch circle Figure16.

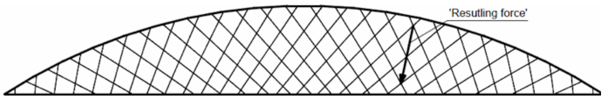

Fig. 16. B. Brunn and F. Schanack net construction scheme

Hence, and in order to simulate a similar structural behavior in the network arch configuration, Brunn and Schanack have defined that the first intersection between hangers below the arch should aim the radii of the arch circle [1, 2]. This way, the only variable involved is the angle between hangers when they cross each other, as illustrated in Figure 17. Here, the hangers are placed with equal space along the upper chord. Throughout this investigation, the angle marked in grey will be the key variable.

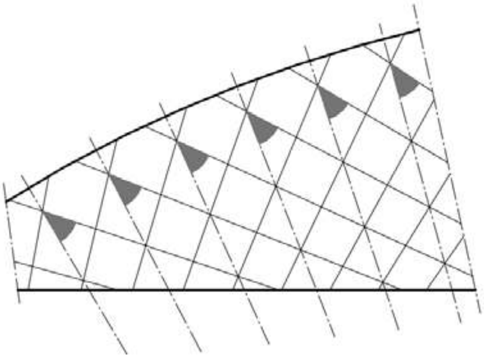

Fig. 17. The variable involved

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. 22 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 bending moment as in Figure 20.

The hanger angle variation does not appear to significantly influence the tie beam axial force

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Figure 23. Bending moments along the beam decreases with increasing angle in Figure 21.

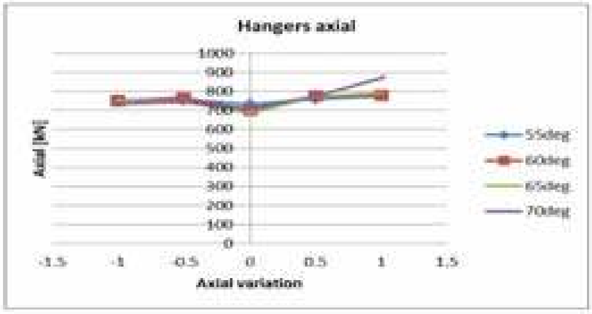

Fig. 18. Axial force variation in hangers in inclined hanger system with variable slope depending on the angle variation

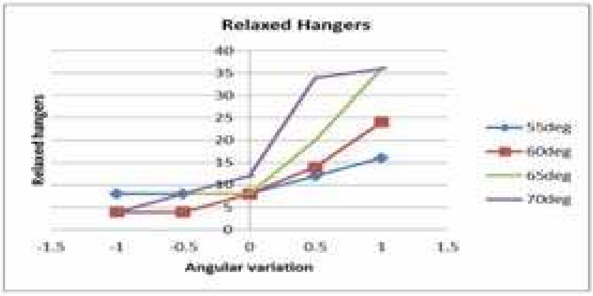

Fig. 19. Number of relaxed hangers in inclined hanger system with variable slope depending on the angle variation

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.

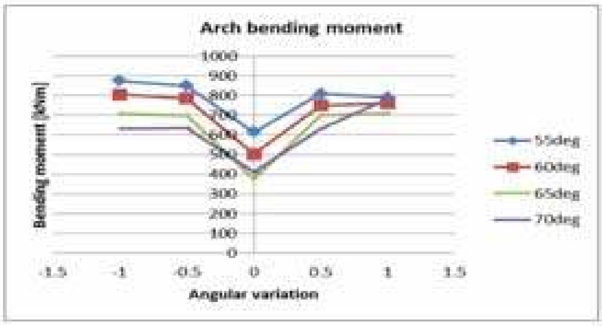

Fig. 20. Bending moment variation in arch in inclined hanger system with variable slope depending on the angle variation

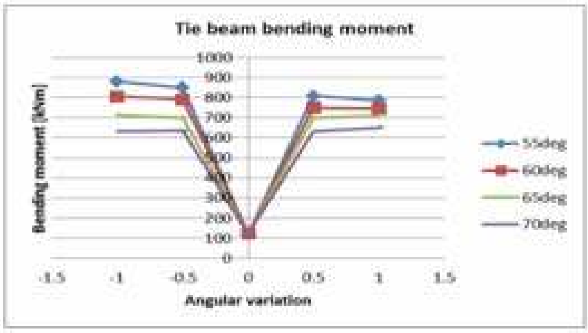

Fig. 21. Bending moment variation in tie beam in inclined hanger system with variable slope depending on the angle variation

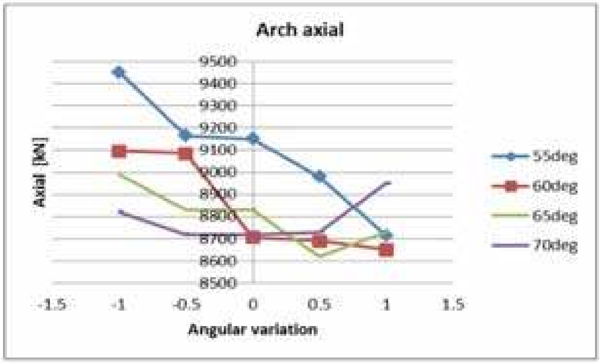

Fig. 22. Axial force variation in arch in inclined hanger system with variable slope depending on the angle variation

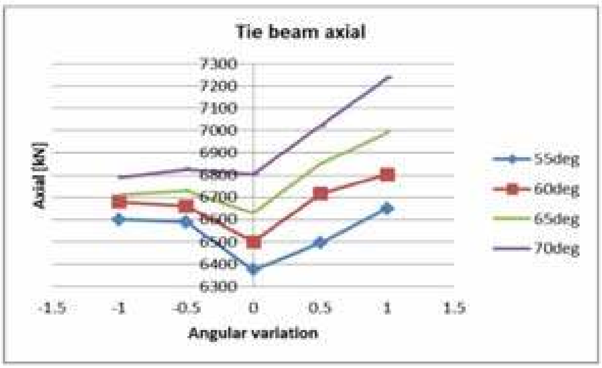

Fig. 23. Axial force variation in tie beam in inclined hanger system with variable slope depending on the angle variation

Originality and practical value

The research conducted by author shows that both nets could be recommended for the practical implementation, and difference between the values of strength criteria of superstructure elements makes about 5%. It may be said that the Brunn-Schanack net provides somewhat less stress value

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over the top chord (since it generally provides steeper hanger inclination angles), while the Tveit net allows reduction of maximum stresses in hangers and bottom chord of superstructure.

Conclusions

Hanger inclination angles

Following key parameter at the superstructure design is value of hanger inclination angles with respect to the top chord. Considering fatigue, a crossing angle slightly bigger than 45° will give best results, whereas small maximum internal forces occur for angles of about 55°.Results of the research conducted by author show that the best recommended range of values of hanger inclination angle with respect to the top chord makes 55-70 degrees.

Too small angles (<45–50°) result in increased forces in hangers, in addition, at the extreme shallow inclination angles, net is overly condensed to the middle of superstructure, which in turn impairs its static performance.

When angle values tend to 90°, the system shows increase in strain-stress state indices of superstructure elements (due to the system tendency to work as the configuration with vertical hangers).

Number of hangers

Important criterion of the inclined ties system performance evaluation is determination of number of hangers, panel pitch over the top chord. Figure 25 shows the curve of effective superstructure element stress coefficient vs. number of hangers.

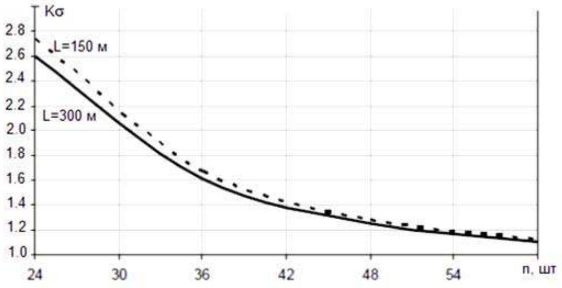

Fig. 24. Curve of superstructure strain-stress state indices vs. number of hangers

Relationship between the number of hangers and superstructure strain-stress state is not linear, but rather hyperbolic with expressed asymptote. Further reduction of number of hangers results in increase in the rate of change of superstructure strain-stress state criteria. The hangers and hanger connections 100 m network arch should be equipped with about 48 hangers per arch plane, which has economical and structural reasons. The extra costs caused by additional hangers and their connections have to be balanced against the material costs that can be saved due to smaller internal forces in arches and tie.

Generally, tied-arch bridge superstructures with the inclined hangers are very efficient systems, and under most circumstances, these can successfully compete with other superstructure configurations even in case of relatively long (400–600 m) span length.

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ОСОБЕННОСТИ ПРОЕКТИРОВАНИЯ КОМБИНИРОВАННЫХ АРОЧНЫХ МОСТОВ С ГИБКИМИ НАКЛОННЫМИ ПОДВЕСКАМИ

Цель. В научной работе предполагается провести исследование и анализ конструкции подвесок: а именно – устойчивости арочных комбинированных мостовых систем с гибкими наклонными подвесками, которые пересекают друг друга как минимум дважды. Также необходимо сделать сравнительный анализ с другими видами конструкций подвесок. **Методика**. В работе авторами исследуется большое количество параметров, определяющих их влияние на распределение усилий в арке. В итоге для всех параметров определяются оптимальные значения. На основе этих оптимальных значений разрабатываются рекомендации к проектированию, которые послужат оптимизации проектирования арочной системы. Для исследования этой проблемы авторы используют трехмерную модель конечных элементов и экспериментальным путем определяют наиболее подходящее решение для автомобильного моста с пролетом 100 метров, состоящего из двух стальных арок, расположенных на дороге с двумя полосами движения, и среднего трафика. Расчет виртуального прототипа модели осуществляется методом конечных элементов в программном комплексе Midas Civil. **Результаты**. В исследовании балки моста бетонная затяжка представляется лучшим решением, учитывая работу конструкции сетчатых арок. Но экономические преимущества, основанные на облегченном монтаже, могут привести к тому, что стальная или композитная балки моста будут более выгодной альтернативой. Проектные требования и местные условия каждого конкретного моста будут определять лучший экономический эффект при проектировании. **Научная новизна.** Для обеспечения комфортности пассажиров, стабильности и непрерывности движения пути уменьшаются деформации мостовых конструкций. Сетчатая арка представляет собой жесткую конструкцию с небольшими отклонениями и поэтому удовлетворяет требованиям даже для высокоскоростных железнодорожных дорог. Сетчатые арочные мосты с бетонной затяжкой обычно экономят более половины стали, необходимой для связки арки с вертикальными подвесками и бетонной затяжкой. **Практическая значимость**. По результатам данного исследования конструктивные рекомендации, указанные в статье, приводят к экономии около 60 % конструкционной стали, по сравнению с обычными комбинированными арочными мостами с вертикальными подвесками.

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Ключевые слова: сетчатый арочный мост; вертикальные подвески; наклонные подвески; арка; теории систем подвесок; количество подвесок; угол наклона подвесок

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ОСОБЛИВОСТІ ПРОЕКТУВАННЯ КОМБІНОВАНИХ АРОЧНИХ МОСТІВ ІЗ ГНУЧКИМИ ПОХИЛИМИ ПІДВІСКАМИ

Мета. В науковій роботі передбачається провести дослідження і аналіз конструкції підвісок: а саме – стійкості арочних комбінованих мостових систем із гнучкими похилими підвісками, які перетинають один одного як мінімум двічі. Також необхідно зробити порівняльний аналіз із іншими видами конструкцій підвісок. **Методика**. У роботі авторами досліджується велика кількість параметрів, які визначають їх вплив на розподіл зусиль в арці. У підсумку для всіх параметрів визначаються оптимальні значення. На основі цих оптимальних значень розробляються рекомендації щодо проектування, які слугуватимуть оптимізації проектування арочної системи. У дослідженні цієї проблеми автори використовують тривимірну модель кінцевих елементів та експериментальним шляхом визначають найкраще рішення для автомобільного мосту з прольотом 100 метрів, що складається з двох сталевих арок, розташованих на дорозі з двома смугами руху, та середнього трафіку. Розрахунок віртуального прототипу моделі здійснюється методом кінцевих елементів у програмному комплексі Midas Civil. **Результати**. У дослідженні балки моста бетонна затяжка представляється кращим рішенням, враховуючи роботу конструкції сітчастих арок. Але економічні переваги, засновані на полегшеному монтажі, можуть призвести до того, що стальна або композитна балки моста будуть кращою альтернативою. Проектні вимоги та місцеві умови кожного конкретного мосту будуть визначати кращий економічний ефект при проектуванні. **Наукова новизна.** Для забезпечення комфортності пасажирів, стабільності та безперервності руху шляху зменшуються деформації мостових конструкцій. Сітчаста арка являє собою жорстку конструкцію з невеликими відхиленнями і тому задовольняє вимогам навіть для високошвидкісних залізничних доріг. Сітчасті арочні мости з бетонною затяжкою зазвичай економлять більше половини сталі, необхідної для зв'язку арки з вертикальними підвісками та бетонною затяжкою. **Практична значимість**. За результатами даного дослідження конструктивні рекомендації, наведені в статті, призводять до економії близько 60 % конструкційної сталі, в порівнянні зі звичайними комбінованими арочними мостами з вертикальними підвісками.

Ключові слова: сітчастий арочний міст; вертикальні підвіски; похилі підвіски; арка; теорії систем підвісок; кількість підвісок; кут нахилу підвісок

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